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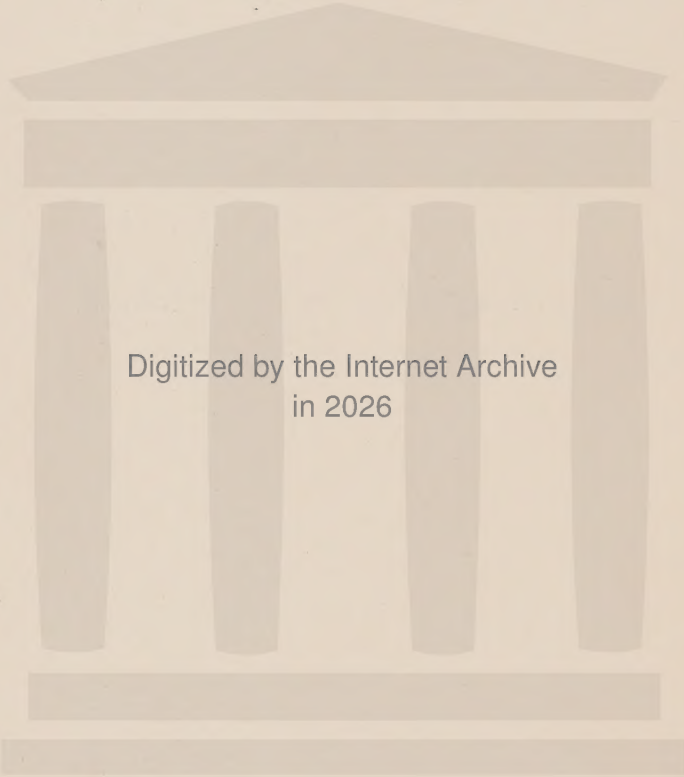
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THE AIRPLANE AND ITS ENGINE



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THE AIRPLANE AND ITS ENGINE

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PREFACE

Such a large number and such a wide variety of books on aeronautical subjects are now being published that the authors of this volume feel that an explanation for adding to the already imposing list may not be out of place.

It appears to us that there has been a distinct gap in aeronautical literature between the purely popular on the one hand, and the highly technical on the other. The first appeals to those interested in the romantic side of aviation, who are eager for stories of famous flights and aviators, and for illustrations of many airplanes, without much regard to their importance as representative types. The other class of books is intended for the technical student, the trained designer, or the highly specialized mechanic, and is therefore of little interest to the general reader. As in everyday life, the multitude and the elite are well provided for, while the "middle class" is largely forgotten.

The present volume is intended primarily for the intelligent middle-class aeronautical readers—that is, for persons interested in acquiring a sound knowledge of the basic facts and theories of the airplane—who still do not desire to give to the subject the intensive study which is essential for the designing engineer or the expert mechanic.

It has been our aim to avoid the use of any but the simplest mathematics, and to require of our readers only such knowledge of physics and mechanics as is acquired in the first two or three years of a high-school course.

For the sake of brevity we have confined ourselves strictly to the modern airplane, avoiding the historical as being of less interest than the contemporary, and omitting all discussion of other types of aircraft, which at present are of secondary importance. We have not attempted to enlarge on the art of piloting, for we believe that this can be learned only by actual practice, nor have we dealt with methods of aircraft operation and maintenance, as these are subjects for the specialist.

No claim is made for originality. What we have related is part of the general knowledge of all aeronautical engineers, and most of it can be found in many places in their writings.

We wish to express our appreciation of the assistance afforded us in the shape of illustrations and data by the National Advisory Committee for Aeronautics, the Air Corps, U. S. A., the Bureau of Aeronautics, U. S. N., and many manufacturers.

We are indebted to several members of the aeronautics staff at the Institute for information and helpful suggestions, and particularly to Mr. Manfred Rauscher, who also made the diagrams and calculations in the chapters devoted to the airplane. Our thanks are due also to Mr. Frank M. Bondor, one of our graduate students, who made most of the power plant drawings and diagrams. The faithful and intelligent assistance of our secretary, Miss Carolyn P. Butts, has been of the greatest value, as has been also the cooperation of the publisher's staff.

CHARLES H. CHATFIELD.

C. FAYETTE TAYLOR.

September, 1928.

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THE AIRPLANE AND ITS ENGINE

CHAPTER I

THE ESSENTIAL PARTS OF THE AIRPLANE

Aircraft, in general, are divided into two classes—those that are supported by the lifting power of gas, and those that are kept up by the action of moving air. Aircraft of the first class are called *lighter than air*, and those of the second class, *heavier than air*. The fundamental difference between the two kinds is perfectly apparent in the two familiar toys, the balloon, which will rise even in a calm, and the kite, which will fly only in a wind.

Among heavier-than-air craft, the only kind that has so far gone beyond the experimental stage is the *airplane*. This is a heavier-than-air craft supported by rigid wings which do not move with reference to the rest of the machine. Aircraft with flapping wings are called *ornithopters*, and those with rotating wings, *helicopters*.

An airplane, like any other vehicle for the carrying of passengers or freight, has four essential parts—a means of support, a means of propulsion, a means of control, and a container for the load which is carried. The airplane is supported by the *wings*, it is propelled by the *power plant*, it is guided by its *control surfaces*, and it carries its load in the *body* or *fuselage*. The fuselage usually carries a *landing gear*, which supports the machine on the ground. Let us now describe briefly these four essential parts as we find them in a typical airplane.

The Wings.—The wings, the most conspicuous part of the airplane, are light structures of wood or metal which extend out on each side of the body like those of a bird or flying insect. Their function is to push downward on the air as they move

through it; that is, they transmit the weight of the airplane to the air. This is only another way of saying that the air pushes up on the wings and so supports the whole machine. This push or lift of the wings is the secret of the support of the airplane. This phenomenon will be studied in some detail in the next chapter.

In view of the importance of the wings, it is not surprising that their arrangement determines the names of the different classes of airplanes. If an airplane has only one wing on each side, like a bird, it is called a *monoplane*. Such an airplane is shown in



FIG. 1.—The Fokker monoplane. The type in which Lieuts. Hegenberger and Maitland made the first flight from California to Hawaii. (Courtesy Materiel Division, U. S. Army Air Corps.)

Fig. 1. If there are two wings on each side, as illustrated in Fig. 2, the machine is called a *biplane*, and if there are three, then the machine is a *triplane*. Sometimes one wing, usually the upper, is much larger than the lower, as in the machine shown in Fig. 3, and then the airplane is known as a *sesquiplane*, literally “one-and-a-half plane.”

A few more terms used in discussing wings may now be defined. The length of a wing from the tip on one side of the machine across to the tip on the other side is called the *span*, and the distance from the front or *leading edge* to the rear or *trailing edge* is called the *chord*. The vertical distance between

one wing and another is called the *gap*, and the distance by which one is set forward of the other is called the *stagger*.



FIG. 2.—The Wright Apache biplane. (Courtesy Wright Aeronautical Corp.)



FIG. 3.—A sesquiplane—The Bellanca Roma. (Courtesy Pratt & Whitney Aircraft Co.)

Naturally, these last two terms apply only to biplanes and triplanes. If the tip of the wing is higher than the middle, the wing

is said to have *dihedral*, and the *dihedral angle* is that between the surface of the wing and the horizontal, as seen from the front. *Sweepback* is the angle, if any, between the wings and a perpendicular to the longitudinal center line of the airplane, as seen from

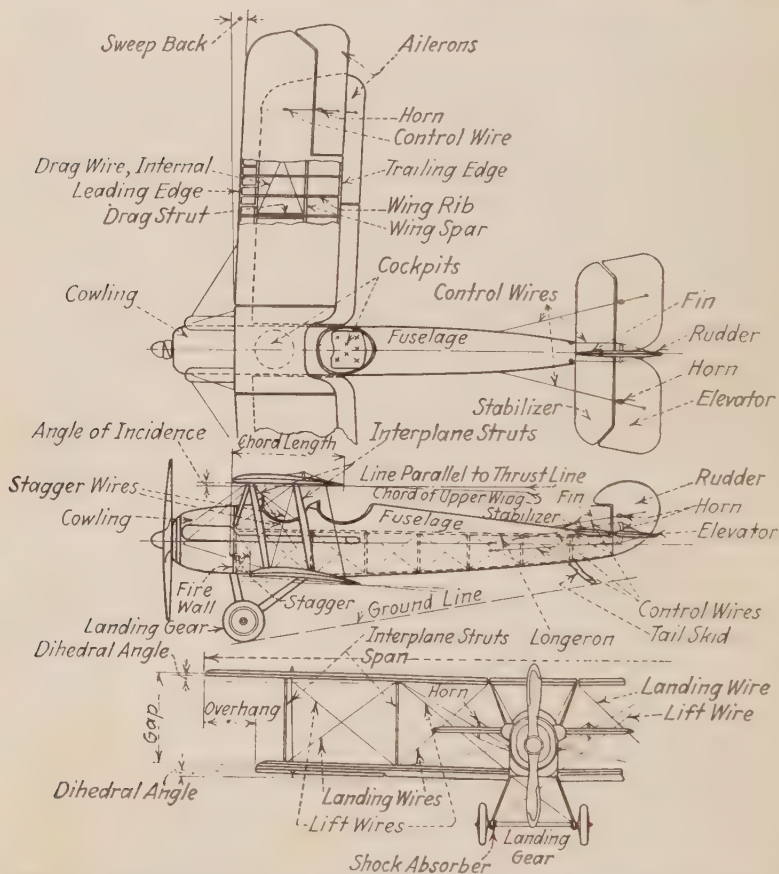


FIG. 4.—Nomenclature of airplane parts. (Courtesy National Advisory Committee for Aeronautics.)

above. Figure 4 illustrates these and other terms in airplane nomenclature.

The Power Plant.—The most conspicuous parts of the power plant, the next essential of the complete airplane, are the *engine* and the *propeller*, though there must be also a fuel-supply system,

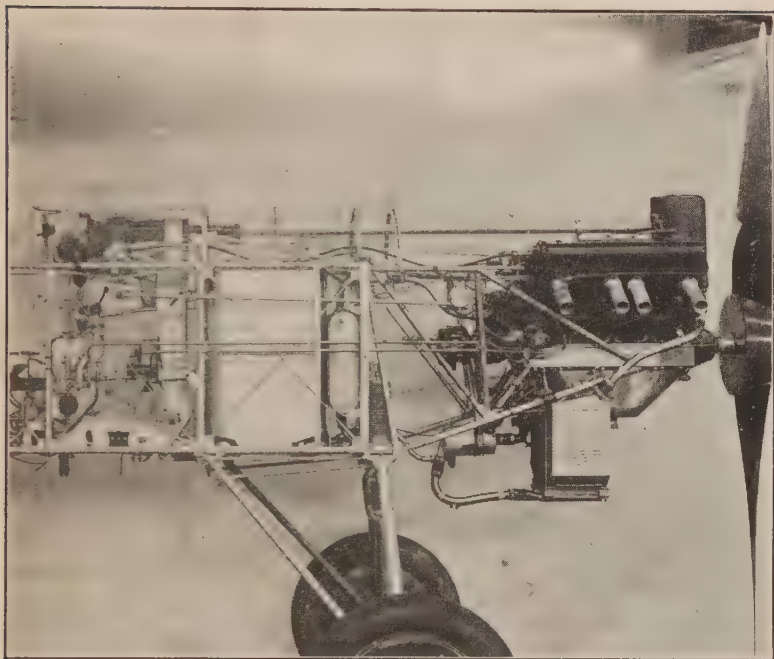


FIG. 5.—Airplane power plant. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)



FIG. 6.—Pusher airplane. (*Courtesy Massachusetts Institute of Technology.*)

an oil supply, a system of engine controls, and a cooling system. Figure 5 shows these parts as installed in an airplane. The engine is ordinarily of the internal-combustion type, like that in



FIG. 7.—Rudder and elevator of a typical airplane. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)

an automobile. The propeller is essentially a device for pushing the air backward and, consequently, for pushing itself forward, together with the airplane to which it is attached. It may be

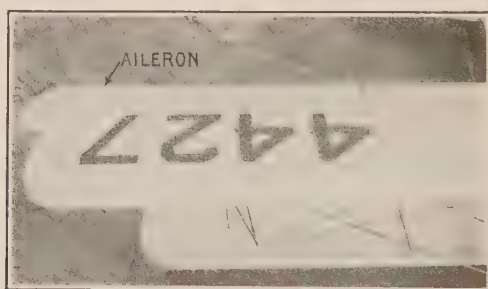


FIG. 8.—Wing tip and aileron. (*Courtesy Boston Airport Corp.*)

regarded as a pair of twisted wings revolving about a central axis, driven by the shaft of the engine to which it is attached.

Usually, the propeller is at the front of the airplane, as shown in Fig. 5, and pulls the rest of the machine after it. An airplane

with this arrangement of power plant is called a *tractor*. If, as is sometimes the case, the propeller is at the rear and pushes the machine, the airplane is called a *pusher*. Such an airplane is illustrated in Fig. 6.

The Controls.—The airplane must have a *rudder* which steers it like the rudder of a ship, and it must have other controls to guide it in other than horizontal paths. To control the vertical motion of the airplane, a second control surface, called the



FIG. 9.—Fuselage of the Vought Corsair. (Courtesy Chance Vought Corp.)

elevator, is provided. Like the rudder, it is placed at the extreme rear of the airplane, but unlike the rudder, it is horizontal and not vertical. The elevator is then really nothing more than a horizontal rudder. Figure 7 shows the rudder and elevator of a typical airplane.

To enable the pilot to roll or bank the airplane, a third set of control surfaces is provided which forms part of the rear of the wings at their tips. These *aileron*s, one of which is illustrated in Fig. 8, are so connected that when one is turned up, the other is turned down: thus, one wing tip is raised and the other lowered.

The action of all these controls, and the mechanism by which the pilot operates them, will be considered in detail later.

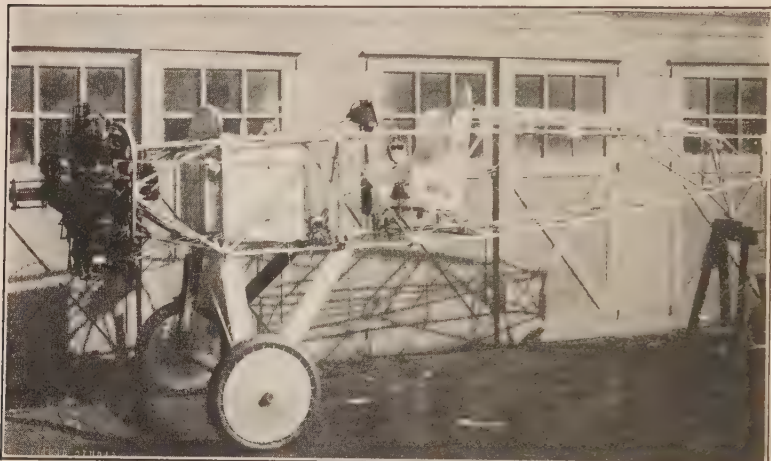


FIG. 10.—The Apache fuselage, uncovered. (Courtesy Wright Aeronautical Corp.)



FIG. 11.— Airplane landing gear. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

The Fuselage and Landing Gear.—The fuselage of an airplane serves several purposes. It houses the crew, the passengers, and

the other load; it usually carries the power plant and supports the tail surfaces. In reality, it is nothing more than a long box, large enough to contain the necessary installations and at the same time properly shaped and not so large as to offer excessive wind resistance. The fuselage of a widely used two-seater

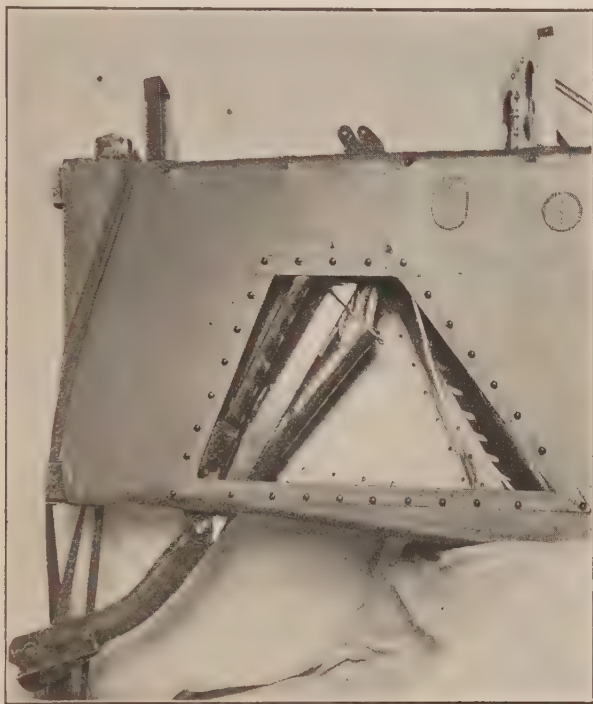


FIG. 12.—Airplane tail skid. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

airplane is shown in Fig. 9, without the wings and tail surfaces, and another typical fuselage is shown uncovered in Fig. 10.

The landing gear usually consists of a pair of wheels carried from the fuselage by a framework of long, hollow tubes called *struts*, an arrangement such as is shown in Fig. 11. In addition to this main landing gear, a support is needed at the rear of the machine. This is the *tail skid*, which, as shown in Fig. 12, is little more than a stick which projects downward and backward

from the bottom of the fuselage and slides along the ground as the airplane rolls along.

As far as flying is concerned, the landing gear is merely a necessary evil. It supports the airplane on the ground and enables it to travel over it at a low speed, but in the air it only adds resistance. It is, therefore, made as small and light as possible.

CHAPTER II

THE WING

Before beginning the study of the airplane itself, let us consider briefly the medium in which it moves and by which it is supported. Air is a mixture of gases, of which oxygen forms 21 per cent by volume. The remainder of the volume is composed chiefly of nitrogen, though other gases, and water vapor, are present in small proportions. The oxygen is a vital need not only for the pilot but also for the engine, as will be explained in the discussion of engine fundamentals. For the present, our chief interest is in the physical properties of the air.

Air and Its Motion.—Air, like all gases, has neither a definite volume nor a definite shape; it will completely fill any container in which it may be placed; nevertheless, it has mass and weight. The upper layers of the earth's atmosphere, therefore, press down on the lower ones, with a pressure which, though small at high altitudes, amounts at sea level to 14.7 lb. per square inch. The air pressure acts in all directions, both inside our bodies and outside, so that we are not conscious of it, but its reality may easily be demonstrated by any one of several simple experiments.

In studying the airplane, we are most interested in the mass of the air, and this is by no means insignificant, for a mass of air which occupies a volume of 1 cu. ft. at sea level has a weight of 0.076 lb. The air at sea level is, therefore, said to have a density of 0.076 lb. per cubic foot. At higher altitudes, where the pressure is less, the density is also less, and at an altitude of 10,000 ft., for example, it is only 0.0565 lb. per cubic foot.

Newton's first law of motion tells us that every body will continue to remain at rest, if it is already at rest, or in motion in a straight line, if it is moving, unless some force acts to compel it to change its previous state of rest or motion. Since air has mass, it is a "body" in the meaning of this law. The common palm-leaf fan is a device for setting air in motion, and any one who has

been obliged to use one on a warm day will readily admit that it takes a very definite force to persuade the air to move. Similarly, one who has tried, perhaps unsuccessfully, to hold an umbrella in a high wind can easily believe that no inconsiderable force is needed to stop or turn aside moving air.

All motion is purely relative; that is, a body can be said to move only with reference to some other body. For example, if a man sits in his seat in a railway train which is moving forward at a speed of 4 miles an hour, he is moving at 4 miles an hour relative to the ground, but he is not moving at all relative to the car. If, however, he walks backward down the aisle of the car at 4 miles an hour, he is then not moving with respect to the ground, although he has a speed of 4 miles an hour with reference to the train. When the airplane is in the air, the relative motion of the air and the machine is the same whether the airplane moves and the air stands still or the air moves and the machine stands still.

Newton's third law states that to every action there is an equal and contrary reaction. The function of the wing of an airplane is to deflect downward the air which strikes it. To do this, the wing must push downward on the air, for the air, as we have seen, can be turned aside only by a force. The action is then the force which the wing exerts on the air, and the reaction is an equal and opposite force with which the air pushes up on the wing. When a certain volume or quantity of air has been pushed down by the wing, it naturally escapes out of reach, and as the wing must always be pushed up by the air if it is to support the airplane, it must have a new volume of air upon which to push down: therefore, the wing must continually move through the air so as to have always a new supply on which to act. It is for this reason that an airplane cannot stay up unless it is moving with reference to the air. In visualizing the motion of the wing through the air, we must always remember, therefore, that the wing is not simply sliding through the air; it is constantly pushing down on it, so that behind the airplane the air is not flowing straight back but somewhat downward as well. If the air is not moved downward, the wing does not lift the airplane.

The Airfoil.—In discussing the wing alone, without considering the rest of the airplane, it is customary to speak of the wing as an *airfoil*, which may be defined as a body upon which the motion

of the air produces a useful reaction. Unfortunately, the reaction of the air on the airfoil is not entirely a useful force; that is, it does not act purely to support the airfoil in the air. The force of the air on the airfoil is directed backward as well as upward, for the airfoil, like any other body, has air resistance. The airfoil differs from other bodies in that the air exerts a useful force on it, as well as a harmful one. On a body such as an airplane wheel, which, of course, is not an airfoil, there is no useful air reaction at all.



FIG. 13.—Cross-section of a typical airfoil.

A typical airfoil is shown in the sketch (Fig. 13). It will be noted that it is not a flat surface, nor is it an extremely thin one, as it has been found by long experience that some curvature and some thickness are essential if the properties of the airfoil are to be good. The top curve of the airfoil is known as the *upper camber*, and the lower curve is called the *lower camber*. Although the use of the word *camber* implies that the surface is curved, the term is nevertheless employed even with reference to a flat lower surface.

Airflow and Lift.—When a moving stream of air encounters an airfoil, part of the air passes above, and part passes below, as shown in Fig. 14. The direction of the airflow may be found

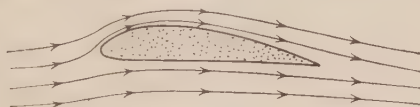


FIG. 14.—Streamline flow past an airfoil.

by experiment on a model airfoil, if smoke is discharged into the air ahead of the airfoil or if very light threads are allowed to trail in the wind. This sort of flow, the stream of air separating smoothly at the leading edge of the airfoil and joining again at the trailing edge without much disturbance, is known as *streamline flow*, and the lines which indicate the direction of the air are called *streamlines*. If the body across which the air is flowing is a symmetrical one, as shown in Fig. 15, then the

direction of the air after it leaves the body is just the same as it was before it struck the body, and the resulting force on the body acts straight back. If an airfoil is placed in the wind at an angle, as shown in Fig. 16, then the air leaving the wing flows somewhat downward. This downward turning of the wind is known as *downwash*, and because of the downwash, the streamlines, as a whole, curve downward. Recalling Newton's first

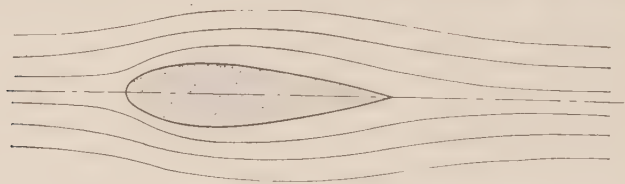


FIG. 15.—Streamline flow past a symmetrical body.

law of motion, it is apparent that there must be some force acting that compels the air to change its direction and to flow off the airfoil downward instead of straight to the rear. As each streamline is approximately an arc of a circle, this force must be continuously acting on the air at right angles to its path. The existence of such force may easily be demonstrated by the experiment of whirling a ball on the end of a string. In



FIG. 16.—Flow past an airfoil inclined to the wind direction.

this experiment, a continuous pull must be maintained on the string if the ball is to travel in a circular path, for as soon as the string is released, the ball flies off straight. The natural tendency of the air to pursue a straight path instead of following a curved one as it passes over the airfoil means that the portion of it on the upper side is constantly pulling away from the wing, while that on the lower side is pushing against it. As a result of this action, the air above the wing is exerting a partial suction

on its upper surface, while that below is exerting an additional pressure on the lower surface. The pressure of the air against the upper surface of the airfoil is then less than the normal atmospheric pressure, while that on the lower surface is more. The result of this is that the moving air tends to pull upward on the upper surface and to push up on the lower. There is, in addition, a definite friction, known as *skin friction*, between the air and the airfoil, so that the air pulls backward on both surfaces, and there is also a backward force caused by the impact of the air against the leading edge.

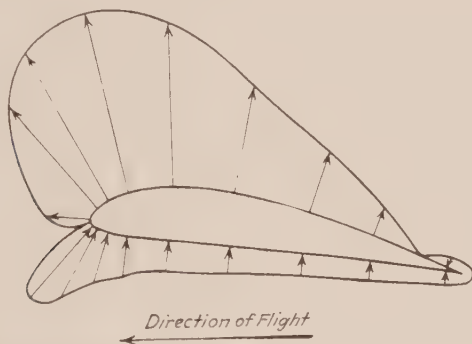


FIG. 17.—Distribution of pressure and suction on an airfoil.

While the streamline curves are approximately arcs of circles, they are not exactly so, and the curvature really varies from one point to another. Since the curvature changes, the force required to make the air follow the curve also changes, for a greater force is needed for a sharp curve than for a more gentle one. This means that neither the suction on the upper surface nor the pressure on the lower is uniform over the area upon which it acts. The curvature of the streamlines is sharpest over the upper leading edge of the airfoil, and it is here that the intensity of suction is greatest. The diagram in Fig. 17 shows the distribution of pressure over the two surfaces of the airfoil. The length of the arrows indicates the intensity of pressure; where the arrows are long the pressure is great, and where the arrows are short, it is small.

The total suction, or deficiency of pressure, on the upper surface is considerably more than the total excess pressure on

the lower one. For a typical airfoil at a moderate angle of attack, the suction on the upper surface may account for 70 per cent of the total force, while the pressure on the lower surface contributes only 30 per cent.

Both the intensity and the distribution of pressure and suction vary with the attitude of the wing to the moving air. Any

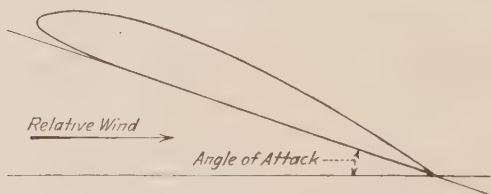


FIG. 18.—Angle of attack.

particular attitude of the airfoil is designated by the angle of its chord to the direction of the relative wind. This angle is called the *angle of attack* and is indicated in Fig. 18. When the angle of attack of the wing is increased from a small value, the curvature of the streamlines becomes sharper, and the angle of downwash increases. The force exerted by the air on the airfoil

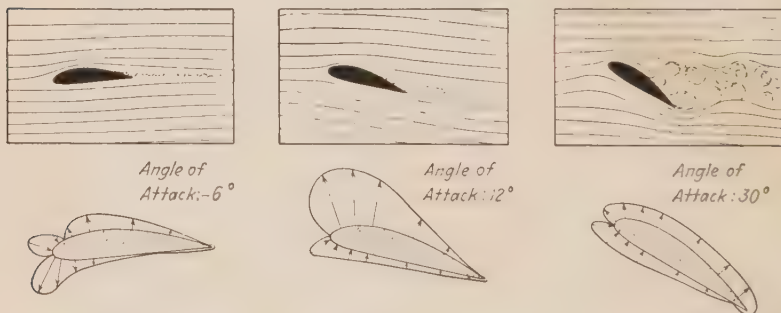


FIG. 19.—Change of airflow and pressure with angle of attack.

naturally increases, also. The upper row of diagrams in Fig. 19 shows how the character of the streamline flow over the airfoil changes with the angle of attack, the shaded areas indicating regions of turbulent flow. The lower row shows the corresponding changes in pressure intensity and in pressure distribution. It will be noted that after a certain angle of attack is passed, there

is a definite alteration in the character of the flow over the upper surface of the wing. The streamlines break away from the surface, and the air close to the wing becomes turbulent instead of flowing along in smooth streamlines. This region of air is then filled with eddies and vortices, and the flow at any one point varies constantly, both in direction and in velocity. As soon as turbulence appears, the suction "breaks down" to a large extent, for the air pressure in the turbulent region is approximately that of the atmosphere. The total force on the surface is consequently reduced. The angle of attack at which this phenomenon first appears is known as the *critical angle* or *burble point*.

Resultant Force and Center of Pressure.—The aggregation of small individual pressures acting all over the surface of the wing can be replaced for purposes of discussion and analysis by a single force known as the *resultant*. The magnitude of this resultant is equal to the sum of the magnitudes of all the individual forces, and its direction is the average of the directions of the little forces, with due allowance for the greater importance of the larger individual forces in determining the direction of the resultant.

This replacement of individual forces by an equivalent resultant is analogous to the process of weighing an automobile upon a platform scale. The automobile exerts four individual forces upon the scale, one for each wheel, but the indicator of the scale reads only the resultant of these forces, that is, their sum, and the effect upon the scale of the four individual forces is exactly the same as that which would be obtained if these four forces were replaced by a single resultant force. In the automobile, we are much more interested in the total weight than in the weight on each individual wheel, and, similarly, for this part of the discussion on airfoils, we are more interested in the total force which acts on the airfoil than we are in the individual forces.

To represent correctly the total effect of the individual forces it is not enough for the resultant to be correct in direction and magnitude; it must also be correct in location. This may be illustrated by employing the analogy of a platform being lifted by ropes at its four corners. Let us assume that these ropes

join in a single rope above, as shown in Fig. 20. The resultant of the individual forces in the four ropes is clearly the single force in the main rope, and it is quite apparent that there can be only one location for this resultant force, for if it is moved in any direction from this location, the platform will immediately tip. In precisely the same way, the resultant of the forces on the airfoil must be properly located. This can readily be done by the engineer. The point at which the line of action of this resultant force intersects the chord of the airfoil is known as the center of pressure, because it is the point about which all the individual pressure and suction forces will balance. The center of pressure is indicated in Fig. 21. If a model airfoil is supported in a wind stream on a pivot which passes through this center of pressure, it will then be in equilibrium and will have no tendency either to tip forward or to tip back.

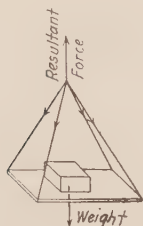


FIG. 20.—Location of resultant force.

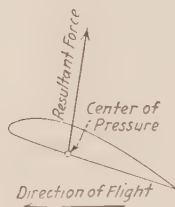


FIG. 21.—Center of pressure on airfoil.

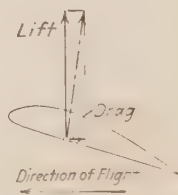


FIG. 22.—Lift and drag forces on airfoil.

Lift and Drag Forces.—It is very convenient to replace the single resultant force by two equivalent forces which act at right angles to each other, as shown in Fig. 22. The first of these forces is called the *lift*, and it may be defined as that component of the resultant force which acts in a direction perpendicular to the direction of the relative wind. The other force is called the *drag*, and it acts at right angles to the lift, that is, parallel to the relative wind. The resultant and its two components evidently have the same relation to one another as the hypotenuse and the two sides of a right triangle. Consequently, the square of the magnitude of the resultant force will always be equal to the sum of the squares of the magnitudes of the two components. Thus, if the lift on a certain model airfoil is 6 lb. and the drag is 1 lb., the resultant must be 6.08 lb.

If an airplane is flying on a level course, as shown in Fig. 23, the lift force acts vertically and supports the airplane, and the drag force acts horizontally backward and resists the motion of the airplane through the air. The lift is, therefore, a useful force, and the drag is a useless one that we must accept in order to get the lift. Since the air offers resistance to any body moving through it, we can under no circumstances obtain a lift force without a corresponding drag. The object of the designer of the airfoil is, therefore, to do the best he can under the circumstances, that is, to obtain the most lift with the least drag. Other things being equal, the best airfoil is, then, that which gives the highest ratio of lift to drag, that is, the highest L/D ratio.

It should be emphasized that the resultant force, the total lift, and the total drag are, to a certain extent, con-

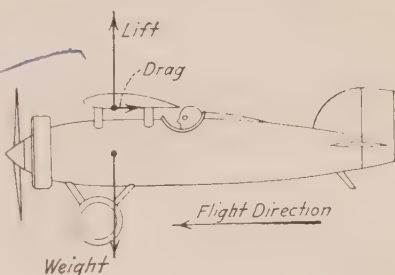


FIG. 23.—Lift and drag forces on airplane.

cepts in the mind of the aeronautical engineer and cannot be said to exist at any one place. The actual forces are the innumerable pressures and suctions distributed over the whole area of the wing, and the resultant force and, consequently, the lift and drag components are to be regarded chiefly as convenient ways of representing this aggregation of very small individual forces. The individual pressure and suction forces may be replaced in the discussion by the equivalent resultant force, and that, in turn, by the equivalent lift and drag forces, but only one of the equivalent systems of forces can be considered as acting at a time. Since the individual forces depend on the angle of attack of the airfoil, so also do the resultant and its two components.

Dependence of Lift and Drag upon Angle of Attack.—While there is a very definite relationship between the magnitude of the lift and drag forces and the angle of attack, this relationship cannot be expressed by a mathematical equation. In general, the lift increases when the angle of attack is increased from some small angle up to the critical angle or burble point, and after that it decreases. By properly adjusting the angle of attack, the lift

can be made zero, though the angle for zero lift is generally one less than 0° , as shown in Fig. 24. The drag force is never zero no matter what the angle of attack and, unlike the lift, does not decrease when the critical angle is passed. The most convenient

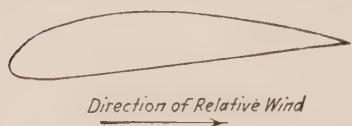


FIG. 24.—Airfoil at angle of zero lift.

way of expressing the relationships of lift and drag to angle of attack is by means of curves or graphs, as in Fig. 25. Here the values of the angle of attack are shown on the horizontal scale, and the corresponding values of lift and drag are shown on the vertical scales. The information necessary for plotting these curves is obtained by measuring the forces upon a small model airfoil in a wind stream of known velocity. Ordinarily, two bal-

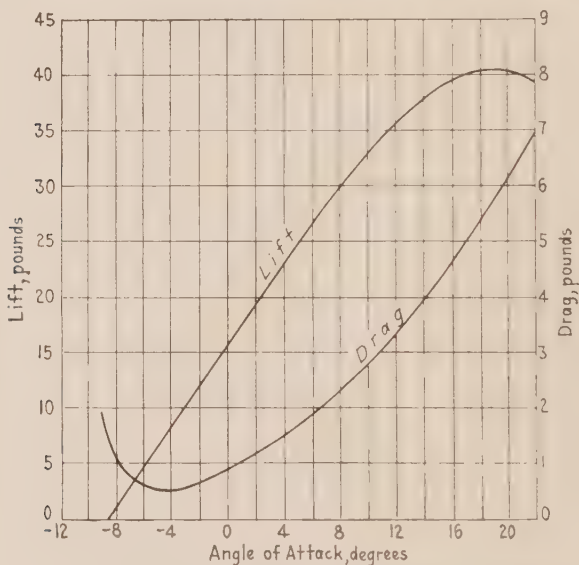


FIG. 25.—Variations in lift and drag with angle of attack.

ances are used, one to measure the force perpendicular to the wind direction, that is, the lift, and the other to measure that parallel to the wind, the drag. The airfoil is first set at a small angle of attack, and the lift and drag for this angle are measured and recorded. The angle of attack is next increased and a

second pair of values of lift and drag obtained, and the process is continued until the critical angle has been passed. The test results would first appear in a table like Table I, the points would be plotted as in Fig. 26, and, finally, curves would be drawn through these points, as shown in Fig. 27.

TABLE I.—RESULTS OF TEST OF MÔDEL AIRFOIL, 36 BY 6 IN.
Air speed, 40 m.p.h.

Angle of attack, degrees °	Lift, pounds	Drag, pounds
-6	-0.231	0.115
-4	0.654	0.091
-2	1.550	0.096
0	2.495	0.119
2	3.364	0.168
4	4.263	0.236
6	5.115	0.319
8	5.930	0.412
10	6.635	0.522
12	7.263	0.635
14	7.624	0.779
16	7.217	1.029

Suppose, now, that for an airfoil which has been tested we wish to know the lift for an angle of attack of $8\frac{1}{2}^\circ$. Upon the chart with the lift curve (Fig. 27), we draw a vertical line at the point on the lower horizontal scale which represents $8\frac{1}{2}^\circ$. From the point where this vertical line intersects the lift curve, we draw a horizontal line as shown, and we note that this horizontal line intersects the vertical scale of lift forces at a value of 6.12 lb. Thus, we find that at an angle of attack of $8\frac{1}{2}^\circ$ the airfoil has a lift of 6.12 lb. The value of the drag for any angle of attack may be obtained in precisely the same manner by using the drag curve instead of the lift curve.

The manner in which the lift of the airfoil varies with the angle of attack is evident from Fig. 27. The lift is zero at an angle of -5.4° . From this point, the lift increases almost uniformly with angle of attack until an angle of 12° is reached. From here the rate of increase is less rapid, and at 14° the maximum

value of the lift is attained. This is the critical angle or burble point, and beyond it the lift decreases. In airfoils of different shapes, the values of the maximum lift may be quite different, and these maximum values may be reached at different angles, but every airfoil has a maximum value at some angle of attack.

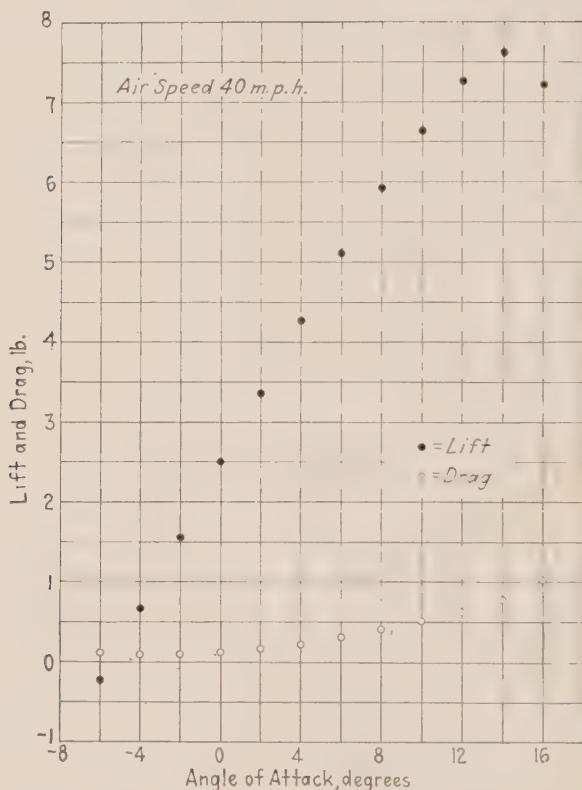


FIG. 26.—Plotted points for lift and drag curves.

The drag curve shows that the drag is a minimum when the angle of attack is -3° . If the angle of attack is made smaller or larger than this, the drag increases.

Effect of Air Speed on Lift and Drag.—The lift and drag of a given airfoil depend not only upon its angle of attack but also upon the speed of the relative wind. The relationship is that the force is proportional to the square of the wind speed. If, for

example, an airfoil at a certain angle of attack gives a lift of 5 lb. when the air speed is 40 miles per hour, then if the speed is doubled, the lift is quadrupled. At 80 miles per hour, the lift would be 20 lb. The same relationship would hold for the drag.

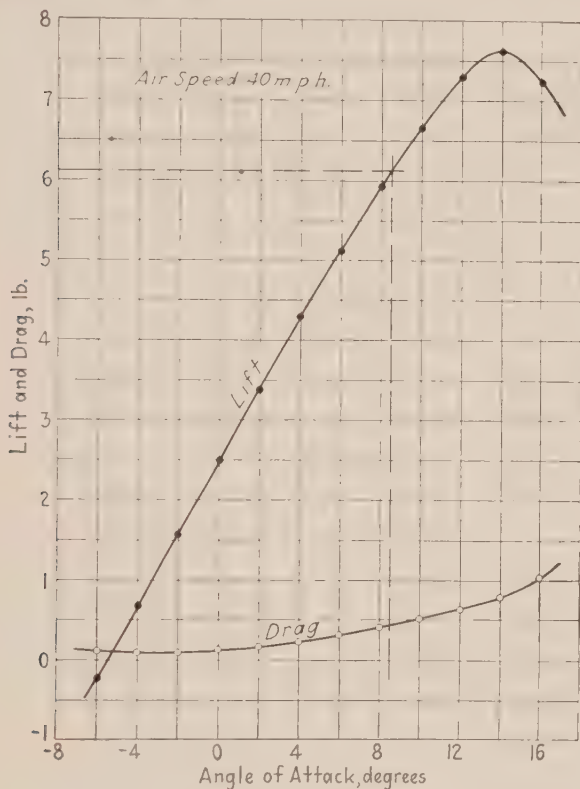


FIG. 27.—Curves of lift and drag.

Lift and Drag Coefficients.—The engineer who is designing an airplane is interested in the lift of a model airfoil under test only as a means of predicting what the wing of his airplane will lift in flight. It has been found by long experiment that, subject to certain corrections, the lifts of two airfoils of the same shape but of different sizes are directly proportional to their areas, if they are tested at the same angle of attack and at the same air speed. Since, if the speeds are different, the lifts are proportional to the

squares of the speeds, the relationship of lift, area, and air speed can be expressed by the equation

$$L = K_y A V^2.$$

In this equation, L is the lift of the airfoil in pounds, A is its area in square feet, and V is the speed of the relative wind in miles per hour. The quantity K_y is a constant which depends upon the shape of the airfoil, the angle of attack, and the density of the air. Figure 27 shows that at an angle of attack of 8° this particular airfoil has a lift of 5.93 lb. The chord of the airfoil is 6 in., and its span is 36 in., so that its area is 216 sq. in. or 1.50 sq. ft. The speed of the relative wind during the test was 40 miles per hour. If the terms of the equation above are rearranged to solve it for K_y , we have

$$K_y = \frac{L}{A V^2}$$

Since the values of L , A , and V^2 are known by measurement and test for this angle of attack, they can be substituted in the equation, so that it reads

$$K_y = \frac{5.93}{1.50 \times (40)^2}$$

Dividing the numerator of the fraction by the product of the two terms in the denominator, a value of 0.00247 is obtained, and so, for this particular airfoil at this angle of attack, the value of K_y is 0.00247. K_y is known as the *lift coefficient*, since it is the characteristic quantity which expresses the lift of a particular shape of airfoil independently of area and air speed.

Evidently, the mathematical operation just performed for the particular angle of attack of 8° can be repeated for all other angles of attack. The only quantities that change during the test are the lift and the angle of attack, so that the value of the lift coefficient K_y can be determined immediately for each angle of attack and plotted as in Fig. 28. With a curve like this, the lift of a wing of any size at any speed can be calculated, as long as the shape of the wing is the same as that of the model airfoil. Suppose, for example, that we wish to know the lift of a wing with an area of 250 sq. ft. at a speed of 120 miles per hour at an angle of attack of 8° . From the curve of lift coefficients, the value

of K_y is found to be 0.00247. Substituting this value and the new values for area and air speed in the lift equation, we have

$$L = 0.00247 \times 250 \times (120)^2 = 8,892$$

The lift of the wing under the conditions given is then 8,892 lb.

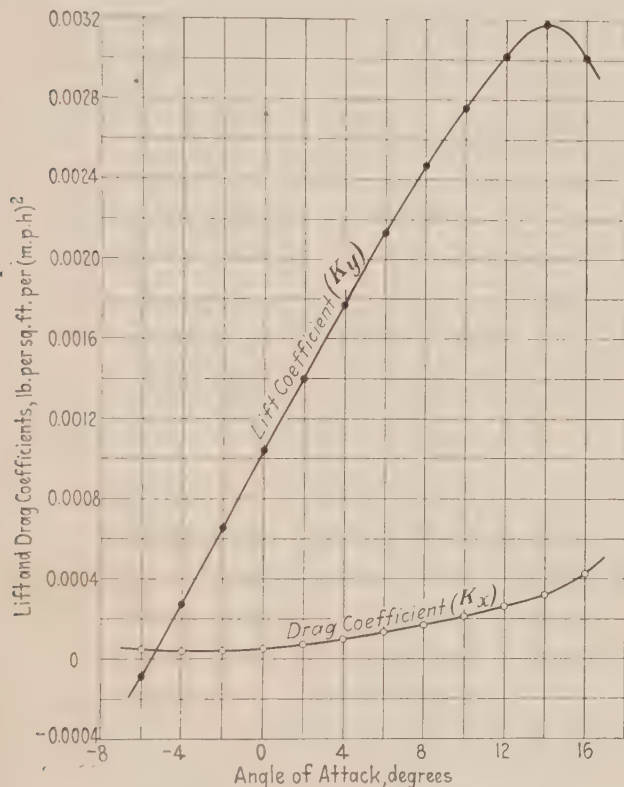


FIG. 28.—Curves of lift and drag coefficients.

The quantity K_y is equal to the lift in pounds when the area of the wing is 1 sq. ft. and the air speed is 1 mile per hour, though no airplane actually has a wing so small or flies at a speed so low.

For the drag force, an equation like that for the lift can be written in the form

$$D = K_x AV^2$$

where D is the drag in pounds, K_x is the drag coefficient, and the other symbols have the same meaning as before. With this equation and a curve of *drag coefficients*, the drag of the full-sized wing can be found in the same manner as is the lift.

Speed and Angle of Attack.—So long as the airplane flies in a horizontal path and does not change its weight, it is evident that the lift of the wing must be approximately equal to the weight of the airplane. Parts of the airplane other than the wings produce lift, but these other lifts are relatively unimportant and may be neglected for the moment. If, as is ordinarily the case, the wings do not change in shape or area, then to each particular speed of flight there must correspond one and only one lift coefficient. If at a given speed the lift coefficient were to increase, the lift equation above shows that there would be more lift than weight, so that the airplane would begin to rise, while if the lift coefficient were to decrease, there would be less lift than weight and the machine would start to descend.

The curve of lift coefficient plotted against angle of attack (Fig. 28) shows that below the angle corresponding to maximum lift there is only one lift coefficient for each angle of attack and, conversely, that there is only one angle of attack for each lift coefficient. It follows directly from this fact that so long as the airplane flies in a level path, and at an angle less than that of maximum lift coefficient, there can be only one angle of attack for a given airplane speed and that at any airplane speed there can be only one angle of attack. The speed cannot be changed without a change in angle of attack, and the angle cannot be changed without a change in speed. If the airplane is to fly more slowly and still in a level path, the angle of attack must increase, and if it is to fly more rapidly without rising, the angle of attack must decrease. Some lift is, of course, derived from other parts of the airplane, and when the angle of attack is large, some is obtained also from the propeller, the axis of which then slopes upward, but these additions do not increase the total lift enough to affect seriously the general relationship between angle of attack and speed.

If the airplane is flying near the angle where the lift coefficient is a maximum, a given lift coefficient may be obtained at either of two angles of attack, one on each side of that corresponding to

the maximum lift coefficient. This is apparent from Fig. 28, where, with a lift coefficient of 0.0030, the angle may be 11.8 or 16.1°. There may then be two different angles of attack at which the airplane speed is the same.

Stalling Angle and Minimum Speed.—When the angle of attack has reached the value at which the lift coefficient is a maximum, the airplane is said to be stalled, and this angle is called the stalling angle. The term "stall" has no reference to the condition in an automobile that is given the same name, for in the stalled airplane the engine may still be running, though probably at a speed a little below normal. The airplane may also be stalled in a glide if the angle of attack relative to the flight path becomes too great.

If the stalling angle of attack is passed, the lift coefficient decreases, and the airplane must increase its speed to maintain itself in the air. The speed corresponding to the stalling angle is evidently the slowest speed at which the machine can fly and hold its altitude, and this speed is known as the minimum speed or the stalling speed. When the airplane is within a few feet of the ground, the lift coefficient increases slightly because of "ground effect," so that the landing speed may be a little less than the true stalling speed.

The stalling speed may be calculated easily from the lift equation, for, since the lift is approximately equal to the weight of the airplane,

$$W = K_{y_{\max.}} A V_{\min.}^2$$

and

$$V_{\min.} = \sqrt{\frac{W}{K_{y_{\max.}} A}}$$

where W is the weight of the airplane in pounds, $K_{y_{\max.}}$ is the maximum lift coefficient, A is the wing area in square feet, and $V_{\min.}$ is the stalling speed in miles per hour. Thus, if an airplane weighs 2,500 lb. and its wings have an area of 240 sq. ft. and are of the airfoil section whose characteristics are given in Fig. 28, then the maximum lift coefficient is 0.00318, and we may write

$$V_{\min.} = \sqrt{\frac{2,500}{(0.00318) \times (240)}} = 57.2$$

The stalling speed is, therefore, 57.2 m.p.h.

An airplane with only the conventional controls is not usually flown at or beyond the stalling angle, for at such attitudes the stability and controllability are likely to be very poor, and the airplane may fall into a spin. A stall followed by a spin has often resulted from an attempt to make an airplane glide in a path not steep enough to give it a velocity greater than the stalling speed. The pilot whose engine has failed should, therefore, resist the temptation to "stretch the glide" to reach a better landing place, for if a spin starts at a low altitude there is little chance to recover from it before the airplane strikes the ground.

Center of Pressure.—It has already been pointed out that the distribution of the individual pressure and suction forces over the

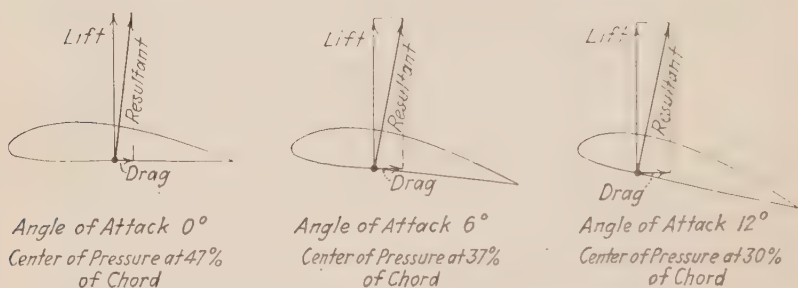


FIG. 29.—Movement of center of pressure with changing angle of attack.

airfoil varies with the angle of attack, and it is natural, therefore, that the location of the resultant force which represents these individual forces should likewise vary with angle of attack. Figure 29 shows the location of the resultant force on an airfoil for three different angles of attack. As the angle of attack increases, the resultant and, consequently, the center of pressure move forward, and if the angle decreases, the center of pressure moves back. This movement of the center of pressure leads to a very important effect upon the behavior of the airplane in flight.

Assume that the airfoil shown in Fig. 29 is pivoted about an axis parallel to its span and 37 per cent of the chord back from the leading edge. If the airfoil is set in a moving air stream at an angle of attack of 6° , it is then balanced on its pivot, for the pivot is precisely at the center of pressure shown in Fig. 29 for an angle of 6° . This balance, or equilibrium, however, is an entirely unstable one, for if any slight disturbance causes the angle of

attack to increase, even by a very small amount, then the center of pressure moves forward, and the resultant force on the airfoil exerts a turning effort about the pivot. This turning effort tends to raise the leading edge of the wing and so to increase its angle of attack still more. The further increase in angle of attack involves another forward movement of the center of pressure, and this, in turn, leads to a still greater increase in angle of attack; the airfoil has no tendency to regain its original attitude. If now by some external means the wing is returned to its original angle of equilibrium, and this time a slight disturbance occurs that causes the angle of attack to decrease slightly, the center of pressure moves back, and a turning effort in the opposite direction is set up. This causes the leading edge of the airfoil to move down, so that the angle of attack decreases, and so on. Since no air stream is entirely uniform in direction, the airfoil will not remain for any appreciable length of time in its position of equilibrium. The airfoil is, therefore, said to be *unstable*, because, if disturbed, it has no tendency to return to its original attitude of equilibrium but rather to depart still more from it.

It is now apparent that a wing cannot fly alone, for however carefully it might be balanced at the start, it is certain that some disturbance would promptly occur to cause the angle of attack either to increase or to decrease. If the former were the case, the angle of maximum lift would soon be passed, and the wing would stall. If the angle decreased, the wing would dive and might even go over on its back. In either event, equilibrium would be lost. It is because of this instability of center of pressure movement that an airplane always has horizontal tail surfaces whose function in flight is to exert a force to counteract the effect of the upsetting force on the wing.

CHAPTER III

AIRFOIL MODIFICATIONS AND ARRANGEMENTS

In the previous chapter, the characteristics of a typical airfoil were discussed, and no reason was given for choosing this particular shape of airfoil instead of some other or for using the airfoil alone or in combination with other airfoils. Airfoil characteristics are profoundly affected, however, both by changes in shape and by the presence of other airfoils, and these effects will now be considered in some detail.

Changes in Shape of Cross-section.—The most important of the possible modifications in the shape of the cross-section of an airfoil is in the curvature or camber of the upper surface. As



Fig. 30.—Modification of upper camber of an airfoil.

might be expected, a sharper curvature of the upper surface compels the stream lines to curve more sharply and so leads to an increase in the intensity of the suction forces. Of the two airfoils shown in Fig. 30, that on the right will develop the higher maximum lift coefficient. It will, however, have a higher drag coefficient.

The effect of an increase in the curvature of the lower surface is like that of an increase of the curvature of the upper surface but smaller in magnitude. As the lower surface of the wing is made more concave,

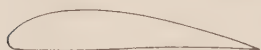


Fig. 31.—Airfoil with nearly flat lower surface.

the lift tends to increase, and again this increase in lift is accompanied by an increase in drag, but in this case the increase in drag may more than offset the advantage due to the increase in lift. Many wings have a lower surface which is flat, or nearly so, as shown in Fig. 31. These wings, in general, have lower lifts than those with concave lower surfaces, but they

have lower drags, also, and so are more widely used. It would be entirely possible to make the lower surface of the airfoil convex, that is, curved downward, as shown in Fig. 32. A change of this sort decreases the drag still more, but it decreases the lift, also, and a lower surface of this shape is not generally used except in connection with an upper surface of pronounced curvature.

Changes in curvature of the two surfaces of the wing cannot be made without corresponding changes in over-all thickness. In general, the thicker the wing the higher its lift, particularly the maximum lift, and the higher its drag. It was formerly believed that in order to have a low drag, the wing must be quite thin, but airfoil research work in the last few years has resulted in a number of shapes of considerable thickness but still with low drag. A typical airfoil of this group is the Clark Y, which is now widely used.

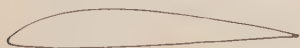


FIG. 32.—Airfoil with convex lower surface.



FIG. 33.—Airfoil with upturned trailing edge.

One more interesting effect of a change in the shape of airfoil cross section is worth mentioning, although it is a modification not often found in practice. This consists in turning up the trailing edge of the wing, as shown in Fig. 33; it results in reducing the movement of the center of pressure. Indeed, it is possible to carry this turning up of the trailing edge to such an extent that the position of the center of pressure is almost the same at all ordinary angles of attack. Such a wing is substantially stable and would have considerable advantages for use in airplanes were it not for the fact that turning up the trailing edge causes a decrease in lift and an increase in drag and so renders the airfoil less suitable from other points of view.

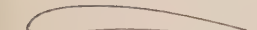
Choice of Airfoil Shapes.—The number of airfoil shapes, or, as they are usually called, airfoils, is now very large. The National Advisory Committee for Aeronautics in five reports on this subject has given the shapes and listed the characteristics of no less than 759 of them. Under these circumstances, one may well wonder how the designer can choose that one of all this number

which is best adapted to a particular airplane. While the subject is too technical to go into at great length, a few of the salient features may be mentioned.

The characteristic to which most attention is usually given is that of maximum lift coefficient, for, since the minimum speed is usually specified, this determines the area of wing which must be used. If the airplane weight has been estimated, and the maximum lift coefficient is known, then the wing area necessary can evidently be calculated by means of the equation of lift already given. If this maximum lift coefficient is low, then the wing area must be relatively large, but if the lift coefficient is high, the wing area may be made considerably smaller. Other things being equal, it is a decided advantage to have a high maximum lift coefficient. If the area of the wing is small, the wing span may likewise be small, and this is ordinarily a distinct advantage in maneuvering the airplane in the air, in handling it on the ground, and in storing it in a hangar. In addition to this, the small wing will generally weigh less than a large one and so will leave a greater margin of weight to be devoted to pay load. The disadvantage of the wing with high maximum lift coefficient is that its drag is likely also to be high, and a high drag means a low maximum speed for the airplane. The use of very thick wings, with high maximum lift coefficients, is, therefore, limited to slow and heavy airplanes, such as bombers and freight carriers.

As has previously been mentioned, it is highly desirable that the L/D ratio of the wing should be high. As the weight of an airplane is fixed, it is evident that the wing drag at any speed is also fixed, and to obtain this drag it is necessary only to divide the weight of the airplane by the L/D ratio corresponding to the particular angle of attack at which the airplane is flying. A wing with a high L/D ratio is particularly required for airplanes which are to fly long distances. The high L/D ratio leads to a low drag, and this, in turn, leads to a low requirement of propeller thrust to overcome the drag. A low thrust means a low engine speed, and this leads to that economy in fuel that is essential if the airplane flight is to be prolonged. It may be said that, in general, it is the wings of medium thickness which have good L/D ratios, and it is these wings which have been so widely used on long-distance airplanes.

TABLE II.—CHARACTERISTICS OF TYPICAL AIRFOILS

Shape	Name	Max. Thickness Per Cent of Chord	Max. Lift Coefficient K_p	Min. Drag Coefficient K_x	Max. L/D
	R.A.F. 15	6	0.00261	0.000030	20
	Curtiss C62	8	0.00233	0.000025	21
	U.S.A. 27	12	0.00346	0.000055	19
	Clark Y	12	0.00318	0.000038	21
	Munk 6	12	0.00286	0.000042	21
	Göttingen 387	15.5	0.00366	0.000060	17
	U.S.A. 35A	18.5	0.00376	0.000076	16
	N.A.C.A. 77	21	0.00294	0.000050	16

For a high-speed airplane, it is vitally important that the minimum drag should be low, so that there may be as little resistance as possible to the advance of the airplane through the air. For this purpose, wings which are distinctly thin are generally chosen. Of these, the C-27 and the C-62, developed by the Curtiss Aeroplane and Motor Company for racing airplanes, are good examples.

To give the reader an idea of the characteristics of airfoils typical of those now in use, there are listed in Table II a number of them arranged approximately in order of thickness. Those with an over-all thickness more than 15 per cent of the chord are classified as *thick*, those whose thickness is between 10 and 15 per cent are considered of medium thickness, and those below 10 per cent are called *thin*.

Changes in Plan Form.—The airfoil may be modified, not only in shape of cross-section but also in plan form, that is, in the shape of the airfoil as seen from above. Here it is the ratio of the span of the airfoil to its chord which is of principal interest. This ratio of span divided by chord is called the aspect ratio. The importance of aspect ratio is apparent from a consideration of what is happening at the tips of an airfoil moving through the air. Since the pressure of the air below the wing is greater than that of the atmosphere, and that of the air above the wing less than atmospheric, there is a constant tendency for the air to flow around the end of the wing from the lower to the upper surface. This flow sets up vortices, or eddies, at the tip of the wing. In the production of these eddies, a considerable increase in drag is involved, because a definite amount of energy is required to set the air whirling, and this energy must be added to that required to drive the wing through the air. Since the eddies are torn off the wing by the forward motion as rapidly as they are formed, their energy is entirely lost, for they die out behind the wing on account of the internal air friction. As every wing must, obviously, have at least two tips, there is no way of avoiding this tip loss entirely, and the next best thing is to have as little tip loss as possible in proportion to the area of the wing. This is accomplished by making the aspect ratio high, that is, by making the span of the wing great in proportion to its chord.

When the lift is high, there is a large difference in pressure between the lower and upper surfaces of the wing, a large flow of air from lower to upper surface around the tips, and, consequently, a large tip loss. For heavily loaded airplanes, therefore, it is essential that the aspect ratio should be as high as possible. The Bellanca airplane *Columbia* which broke the world's endurance record in 1927 has a wing with an aspect ratio of 7, a distinctly high value for airplanes of this type. On the other hand, a racing airplane flying at high speed has a wing which is operating at a relatively low lift coefficient, so that here the aspect ratio is less important.

Some improvement in airfoil characteristics can be made by *tapering* the wings, that is, by making the chord less at the tip than at the center. Tapering is beneficial only if kept within

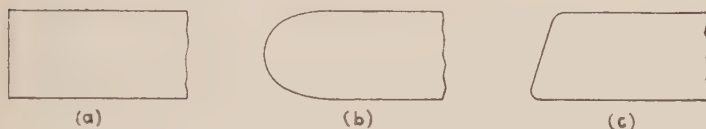


FIG. 34.—Shapes of airfoil tips.

reasonable limits; a wing which was tapered to a point at the tip, for example, would not be so good as one with no taper at all.

Another change that can be made in the plan form of a wing is in the shape of the tips. The simplest and cheapest construction is to cut the tips off square, as shown in Fig. 34 (a). It is rather more common, however, to round them, as shown in Fig. 34 (b), or to *rake* them, as in Fig. 34 (c). Provided that the shape is not extreme, the effects of such modifications are not very great.

Multiple Wings.—Where more area is needed than can conveniently be furnished by a single wing, the obvious procedure is to employ more than one wing. Some of the early experimenters attempted to solve the problem by placing one wing behind the other, in a tandem arrangement. This arrangement was soon abandoned in favor of that with one wing above the other, as in the modern biplane. The biplane arrangement of wings evidently has the advantage over the monoplane that the wings can be more effectively braced and so can be made

lighter to carry a given load. On the other hand, each wing interferes with the flow of air over the other, with resulting loss of lift and increase in drag. There is, likewise, an increase in drag due to the resistance of the bracing which is employed between the wings. In spite of these disadvantages, however, the biplane is widely used, and as it has the added advantage of a smaller span for a given wing area, it is likely that biplanes will continue in use for a long time.

The interference in airflow between the two wings of a biplane arises from the fact that the area of high pressure on the under surface of the upper wing is brought relatively close to the area of low pressure on the upper surface of the lower wing, so that the intensity of pressure on the lower surface of the upper wing and that of the suction on the upper surface of the lower wing are both reduced. Since the larger part of the lift on a wing is due to the suction on its upper surface, this effect is most serious on the lower wing; consequently, while the lower wing contributes nearly its normal share of the drag, it does not contribute its normal share of the lift, and the efficiency of the combination of wings is reduced.

If three wings are used, one above the other, the interference effect is still worse, for the upper and lower wings are subject to the same interference as before, and the center wing is interfered with on both its surfaces, so that it is less efficient than either of the others. While triplanes have occasionally had some popularity, hardly any are now being built.

When the upper wing of a biplane is placed directly over the lower wing, the biplane is said to be *orthogonal*, but when the upper wing is not directly over the lower wing, then the machine is said to have *stagger*. In spite of the structural difficulties that it involves, stagger is very common. Its chief purpose is ordinarily to afford better vision for a pilot who is sitting just behind and below the trailing edge of the upper wing. In military airplanes, it is often difficult, without stagger, to make the machine balance and, at the same time, to give the pilot the necessary vision. The effect on the wing characteristics of positive stagger—the arrangement with the upper wing ahead of the lower—is generally good, while that of negative stagger—upper wing behind lower—is to give lift and drag characteristics

less favorable than those of the orthogonal biplane or of the biplane with positive stagger.

Variable Airfoils.—It has already been pointed out that an airplane must ordinarily be designed for a minimum speed not higher than a certain specified value and that this requirement determines the wing area which must be used and, consequently, imposes a limit on the high speed of the airplane. Once the airplane is in the air and has reached a normal speed, a high lift coefficient is no longer needed. If some means could be devised by which the area of the wing could be reduced or its shape changed in flight so as to decrease the drag, the high speed could be increased without raising the minimum speed. If the decrease in drag involved also a decrease in lift, this would not be serious, for at normal flying speeds there is an ample margin of lift.

At this point it is worth while to consider briefly a third method of modifying the wings of an airplane in flight. This last method has frequently been proposed, and occasionally tried, but as it rests upon a fundamental misapprehension of airfoil characteristics, the results have been uniformly of little value. The idea is that if in some way the angular setting of the wings relative to the fuselage could be varied in flight, the pilot would then have some control over the angle of attack which he does not ordinarily possess. The arrangement is, therefore, known as *variable angle of incidence*, since the angle of incidence is that between the wing chord and the fuselage. Even a very brief consideration of the matter will show, however, that what such a device really accomplishes is not a variation in the angle of attack of the wings but rather one in the angle of the fuselage to the relative wind. It has already been shown that, for a given speed and weight of airplane and an airfoil of fixed shape and area, there can be only one angle of attack at ordinary flying speeds. It is true that there would be some benefit from the ability to change the angle of the fuselage relative to the wind, so that the resistance of the fuselage might be decreased for certain attitudes of the airplane. When the airplane is climbing, the angle of attack of the wings must be more than for level flight at high speed. The fuselage is then at an angle to the relative wind, and its resistance is greater than if it were pointed directly along the flight path. This reduction in resistance, however, is not

enough to be worth the additional weight and complication of the mechanism for changing the angle of incidence.

Varying the area of the wings is perfectly correct in theory but offers the severest practical difficulties. Arrangements for telescoping part of the wing inside the rest might be devised, but it is altogether probable that the necessary mechanism would weigh so much as to overcome any theoretical advantages that might result from its use.

The most promising field for variable airfoils appears to lie in changing the shape of the airfoil in flight. The simplest way of doing this is by using *flaps*, either on the leading or on the trailing



FIG. 35.—Airfoil with flaps on leading and trailing edges.

edge or on both, as shown in Fig.

35. Considering the airfoil as a whole, it is apparent that when a

leading edge flap or a trailing edge flap is turned down, the curvature

of the upper surface is increased and the lower surface is made more concave. This leads to an increase in lift. The increase in drag that accompanies the improvement in lift is not a serious disadvantage, for when the airplane is in normal flight, the flap is not pulled down, and the characteristics of the airfoil are essentially the same as those of the original one without the flap. Thus, the high speed of the airplane is not appreciably reduced. When the pilot desires to land, he pulls down the flap and thus increases the lift coefficient of the wings. This decreases the minimum speed at which the airplane can support itself in the air and so permits the pilot to make a slower and, therefore, a better landing. Under these conditions, the increase in drag caused by the flap may be a real advantage, for when the drag is increased, the airplane can glide into the field at a steeper angle without gaining too much speed.

The use of flaps, however, does entail two definite disadvantages. The first lies in the increased weight of the operating mechanism and the danger that it may fail to work properly at a critical moment. The second is that pulling down the flaps is likely to make the airplane harder to control. The center of pressure on the wings moves as soon as the flaps are pulled down, and this movement, of course, changes the balance of the airplane. At the same time, the flaps when pulled down disturb

the flow of air from the trailing edge of the wing and so reduce the effectiveness of the tail surfaces in correcting for the change of balance, since these surfaces do not work so well in turbulent air as in a region of smooth flow. It is not surprising, therefore, that while many designers have tried flaps, few have continued to use them very long.

One more variety of variable airfoil must be considered. This is the *slotted wing*, which was invented independently by Handley Page in England and by Lachmann in Germany, about 1920.



FIG. 36.—Airfoil with slot.

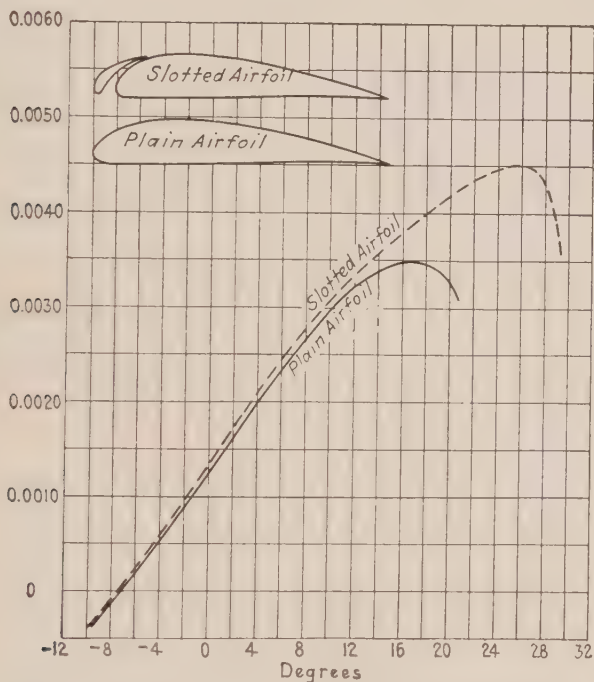


FIG. 37.—Comparative lift curves with and without slot.

Figure 36 shows a cross-section and perspective view of a typical arrangement of this device. The position of the small auxiliary

airfoil in front of the leading edge of the main airfoil is variable, or else some provision is made for opening and closing the slot between the little airfoil and the main one. When the airplane is in normal flight, the slot is closed, or the auxiliary airfoil is pulled back against the leading edge of the main one. When an increased lift coefficient is desired, the slot is opened, or the auxiliary airfoil is moved forward.

Since the pressure on the lower surface of the airfoil is higher than that on the upper, it is evident that as soon as the slot is opened there will be a considerable flow of air up through it. The slot and the auxiliary airfoil are so shaped that the air which passes through is directed backward along the upper surface of the main airfoil. The effect of this additional inflow of air is to postpone the breakdown of streamline flow with increasing angle of attack, that is, to prevent the air over the upper surface of the main airfoil from becoming turbulent as soon as it otherwise would. This means, therefore, that at an angle of attack at which the ordinary airfoil has passed its maximum lift, the lift of the slotted airfoil is still increasing. This is evident from a comparison of the lift curves, shown in Fig. 37, for two typical airfoils, one slotted, and one without a slot. It will be noted that the lift of the slotted airfoil at moderate angles of attack is not materially greater than that of the unslotted one but that the slotted airfoil continues to increase its lift up to a much higher angle of attack. It is apparent, therefore, that of two airplanes of the same weight and wing area, that with slotted wings can maintain itself in the air at a considerably lower flying speed than can the one with plain wings.

The advantages of the slotted wing are not attained without accompanying disadvantages. The additional weight and complication of the mechanism required to operate the slots, or to move the variable airfoil, must be reckoned with. Furthermore, when the slot is closed, or the auxiliary airfoil is close against the leading edge of the main airfoil, the contour of the wing is not quite so smooth as that of a normal wing, so that the drag is increased. This means that the maximum speed of an airplane with slotted wings will not be so high as that of one with unslotted wings of the same area. The reduction in minimum speed has to be paid for by a reduction in high speed. Another disadvantage

of the slotted wing results from the fact that its increased lift is obtained only by increasing the angle of attack considerably beyond that corresponding to maximum lift in a normal wing. Thus, when an airplane equipped with slotted wings comes in to land, the tail of the fuselage hangs abnormally low. As it is not desirable to have the tail skid of the airplane strike the ground much before the wheels touch, it is necessary to carry the wheels at a greater distance below the fuselage than would otherwise be the case, and the resulting additional length of landing-gear struts involves greater weight and air resistance.

Handley Page has recently found it possible to improve his slotted wing by making the operation of the auxiliary airfoil automatic. By mounting this in a certain way, the slot is closed so long as the angle of attack of the main wing is below 12° ; when this angle is passed, the slot opens, and the increased lift is obtained. This is obviously a distinct step forward. The automatic slotted wing makes possible also a marked improvement in the control of airplanes at high angles of attack and is likely to be widely used.

CHAPTER IV

PARASITE RESISTANCE, FUSELAGE AND LANDING GEAR

PARASITE RESISTANCE

Only the wings and tail surfaces of an airplane have a useful air reaction, that is, produce lift. The resistance of all the other parts of the airplane, except the propeller, is a clear loss and is not accompanied by any useful air force. This useless resistance is called *parasite resistance*. It depends upon the shape and size of the body causing it and upon the speed with which the body moves through the air. Naturally, the object of the airplane designer is to keep the parasite resistance just as low as possible, for every added pound of resistance demands an added pound of propeller thrust to overcome it and, consequently, an increase in engine power and in fuel consumption. Good airplane design is quite largely a matter of reduction of parasite resistance.

The parasite resistance of any body can be expressed in the form of an equation like that for the drag of an airfoil. This equation is

$$R = K_p S V^2,$$

where R is the total parasite resistance in pounds, K_p is a resistance coefficient, which, like the drag coefficient of an airfoil, depends upon the shape of the body, and V is the speed of the relative wind in miles per hour. S is the *projected area* of the body in square feet. By projected area is meant the area of the largest cross-section of the body which can be taken in a plane at right angles to the direction of the relative wind.

From the equation, it is evident that the parasite resistance of a body is directly proportional to the square of the air speed; that is, it varies in the same way with air speed as do the lift and drag of an airfoil. While the equation for parasite resistance is in almost precisely the same form as that for airfoil drag, it should

be noted that the area S in the equation of parasite resistance is not the same as the area A in the equation of airfoil drag. The former, as just mentioned, is the projected area of the maximum cross-section, while the latter is that in the plane of the wing chord and, consequently, is much greater. If the angle of attack of the airfoil were 90° , then the two areas would be the same.

Effect of Shape on Parasite Resistance.—As a sort of standard of parasite resistance, it is convenient to consider, first, the flat plate set broadside to the wind. S in the equation is then the area of the plate in the ordinary sense. It has been found by numerous experiments that, under these conditions, the value of the resistance coefficient K_p is 0.0035, so that the resistance of a flat plate 1 sq. ft. in area in an air stream moving at the rate of 1 mile per hour would be 0.0035 lb. The resistance changes somewhat with the shape of the plate, but these variations are not very great.



FIG. 38.—Flow of air past a flat plate.

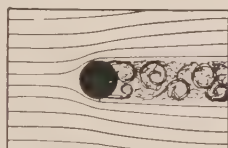


FIG. 39.—Flow of air past a cylinder.

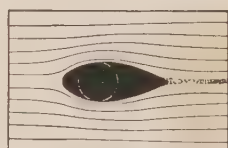


FIG. 40.—Flow of air past a streamline section.

Figure 38 is a diagram of the flow past a flat plate and shows that in the region just back of the plate the air is very turbulent and that in front it has to change direction sharply. The resistance of the flat plate is, therefore, high.

Since round tubing is often used for structural members in aircraft, a good deal of experimental work has been done to determine the resistance of cylinders, for a round tube is nothing more than a long cylinder. From Fig. 39, it is apparent that the flow of air past a cylinder is somewhat smoother than that past a flat plate; the coefficient K_p for cylinders of considerable length is 0.0030. Even around a cylinder, however, the flow of air is not so smooth as might be desired, and a very marked reduction in resistance may be made by adding material to the front and back, as shown in Fig. 40, converting it into what is known as a *streamline* section. The term *streamline* is employed because

the air tends to flow past a section of this shape much more nearly in regular streamlines than it does past a section of any other shape. For a good streamline section, the resistance coefficient may be as low as 0.00015, which means that the resistance of a strut of this form would be only one-twentieth of that of one of the same thickness but of cylindrical cross-section. A strut of square cross section is even worse than one of circular cross-section. One of elliptical cross-section with the short dimension across the wind is better than a cylindrical strut but is still much inferior to one of streamline section.

A single round wire is only a cylinder which has great length in proportion to its diameter and so has about the same resistance coefficient as any other long cylinder. A cable composed of a number of strands, in spite of its rough surface, does not differ much in resistance from a conventional cylinder.



FIG. 41.—Fairing between a pair of round wires.

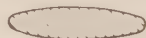


FIG. 42.—Cross-section of streamline wire.

If two wires are placed so that one is directly behind the other, the front one shields the rear one, and the resistance of the two wires together is considerably less than twice that of one wire alone; indeed, if the two wires are close together, the resistance of the pair may be less than that of a single wire. The resistance of a pair of wires may be still further reduced by filling in the gap between them, that is, by *fairing* them, as shown in Fig. 41.

The high resistance of single round wires has caused them to be largely replaced by wires with the form of cross-section shown in Fig. 42. These are known as *streamline wires*, although, since the curvature of the front is the same as that of the back, the section is not a true streamline.

In addition to bodies which, like struts, are very long in proportion to their thickness, it is necessary to consider also those that are solids of revolution, that is, bodies of which every cross-section at right angles to the relative wind is a circle. The sphere is the simplest form of the solid of revolution, and its resistance coefficient is 0.0008. Again, this resistance can be greatly reduced by fairing, and in this way the so-called *streamline body*

is obtained. This has the form shown in Fig. 43. A good streamline body may have a resistance coefficient as low as 0.00011. This coefficient, it will be noted, is even lower than that for a strut of streamline cross-section. For structural and other reasons, it is unfortunately not often possible to design airplane fuselages to a very good streamline form, but it is usually worth while to approach this ideal as closely as possible, as has been done in the bodies of some modern racing automobiles.



FIG. 43.—Streamline body.

The better the form of a streamline body the more is its resistance increased by any slight irregularity in the surface. One experiment showed that the addition of a wire around a streamline body, as shown in Fig. 44, increased the resistance by 50 per cent, even though the diameter of the wire was only one six-hundredth of the thickness of the streamline body. In practice, therefore, the form of the ideal streamline body can only be approximated.

All the resistance coefficients given above were determined with the center line of the body in question pointing directly into the relative wind. If the angle between this axis and the relative wind is not zero, the resistance is increased. For small changes in angle, the increase is not very great. For example, a 5° angle for a streamline strut involves an increase in resistance of 25 per cent, and the same angle for a streamline body gives an increase of 10 per cent. If the angle becomes large, however, the increase in resistance is great. In a streamline strut set at 15° to the relative wind, for example, the resistance is increased by 600 per cent over that with the axis at 0° .



FIG. 44.—A wire around a streamline body.

Another form of body is worthy of brief mention in connection with parasite resistance, because, while it is rarely used on airplanes, it has interesting application in another branch of aero-

nautics. This is the hollow hemisphere shown in Fig. 45. If the concave side of the hemisphere is broadside to the wind, the resistance coefficient is 0.00340, but if the other side is toward the wind, the coefficient is only 0.00086. The Robinson cup anemometer, shown in Fig. 46, takes advantage of this difference. Four of these hollow hemispheres are mounted upon arms which

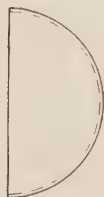


FIG. 45.—Hollow hemisphere.

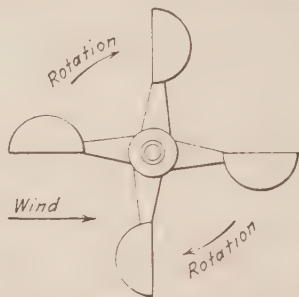


FIG. 46.—Robinson cup anemometer.

rotate about a pivot, and the difference in resistance on the opposite hemispheres causes the device to turn at a rate that depends on the wind velocity.

THE FUSELAGE

The fuselage of an airplane has to perform several functions. It must afford space for the installation of the power plant and for carrying the fuel, the crew, the passengers, and any other useful load. It must have points of attachment for the wings, the tail surfaces, and the landing gear and must be strong enough to carry, without excessive deflection, the loads which are imposed on it at these points. The shape of the fuselage should be one of low air resistance, but interference with vision must be avoided.

Unfortunately, the requirements just stated for a good fuselage are quite contradictory. If the fuselage is made large in cross-section so as to provide ample room for installations and for useful load, the overall size is increased, and the resistance of the fuselage goes up. If the outside of the fuselage curves smoothly from front to rear, with a contour like that of a streamline body, then the structure of the fuselage becomes heavier and much more expensive. A fuselage of circular cross-section has a lower

resistance than one of rectangular cross-section, but this construction increases the cost and weight and interferes with the vision of the pilot, if he sits in an open cockpit. An open cockpit involves additional resistance, but this higher resistance often has to be tolerated, because in many airplanes, and particularly in those designed for military service, an open cockpit is absolutely necessary to give the pilot sufficient vision. The final design of the fuselage, like that of all the rest of the airplane, is, therefore, a matter of compromise, and it can hardly be ideal in any one respect.

Fuselage Shape and Resistance.—From the point of view of resistance alone it would be highly desirable to make the fuselage of the same form as that of the good streamline body illustrated in Fig. 43. For the reasons just mentioned, it is possible at best only to approximate this form. If an air-cooled engine is used, the cylinders not only themselves cause resistance but also disturb the flow of the air over the rest of the fuselage. Experiments conducted on a full-size airplane by the National Advisory Committee for Aeronautics showed the resistance of the fuselage plus that of the engine to be 70 per cent more than that of the fuselage alone. If a water-cooled engine is used, there is still an increase in resistance, for while the engine does not project so much into the wind, it does require the front of the fuselage to be different in shape from that which gives lowest resistance. In addition, there must be a radiator, and wherever this may be placed, it causes an increase in resistance that cannot be avoided except by the use of a radiator of a very expensive and unserviceable type.

In some airplanes, it has been possible to avoid the resistance of an open cockpit by placing the pilot in a closed one, but this involves the possibility of so interfering with his vision as to imply an element of danger. Nevertheless, this problem has been quite satisfactorily solved in a number of instances. If passengers are to be carried, they should be in a comfortable cabin. This cabin usually involves an increase in fuselage height and frequently also one in width, so that the resistance is increased.

The design of the fuselage for a military airplane is often a matter of the greatest difficulty, because it is necessary to install

in a very confined space a large variety of equipment and to arrange this equipment so that each item is accessible to the crew and, at the same time, out of their way. Guns on a rotating mount cause additional resistance, both directly and because of the change that is required in fuselage shape.

A streamline body should taper to a point at the rear, but this shape is ordinarily not possible in an airplane fuselage because of the necessity of providing adequate support for the tail surfaces. If these are to be rigidly held in place, each must be attached to the fuselage at more than one point, and the rear of the fuselage must be large enough in cross-section so that it will not deflect excessively nor vibrate under the loads which the tail surfaces impose on it.

Fuselage Arrangement.—The arrangement of the fuselage in a small single-seater airplane has already been illustrated in Fig. 10 (p. 8). The engine is placed in the extreme nose



FIG. 47.—Cabin monoplane for pilot and four passengers. (Courtesy Fairchild Airplane Manufacturing Corporation.)

and is carried on a framework called the *engine mount*. Just behind the engine is the oil tank, and behind this a *fire wall*, which extends completely across the fuselage from top to bottom. This fire wall is commonly made of two sheets of aluminum or duralumin, with a sheet of asbestos between, and it prevents a

fire in the engine compartment from spreading back to the fuel or to other parts of the fuselage. The fuel tank is usually placed just behind the fire wall. Back of the fuel tank is a cockpit for the pilot. The rest of the fuselage, from the cockpit back to the tail, is ordinarily occupied only by control pulleys and wires.

The arrangement of the fuselage of a larger airplane, designed for a pilot and four passengers, is largely evident from the photograph (Fig. 47). The engine is in front, as before, with the oil tank just behind it, and a fire wall separates the engine compartment from the rest of the fuselage. The seat for the pilot is just back of the fire wall and behind it are the seats for the four passengers. To reduce the danger from fire, the fuel is carried in the wings.

Fuselage arrangements of various types of airplanes are discussed further in Chaps. XIV and XV.

THE LANDING GEAR

The landing gear is provided solely to enable the airplane to travel on the ground. A simple form of landing gear is shown in Fig. 48. It consists of a pair of wheels mounted on a framework of struts and wires. The location of the landing gear depends on the distribution of weight in the airplane, for the wheels must be far enough forward so that the airplane is not in danger of "nosing over" while it is running on the ground, and at the same time they must be far enough back so that there will not be an excessive load on the tail skid. The height necessary for the landing gear depends on the diameter of the propeller and on the characteristics of the wings. It must be enough so that when the airplane is running over the ground with the tail skid off, and the fuselage horizontal, there will be a clearance between the tips of the propeller and the ground of at least 9 in. The landing gear must also be high enough so that when the tail skid is resting on the ground, the angle of the wings to the horizontal is not very far below the angle of attack corresponding to maximum lift. This is necessary, because the pilot ordinarily wishes to land the airplane at an airspeed as low as possible, and to do this it is, of course, necessary for him to fly with the wings at

the angle of attack where they give their maximum lift. It would be undesirable to have the landing gear so short that under these conditions the tail skid would strike the ground while the wheels were still at a considerable distance above it. If the wings were set at a considerable angle of incidence, that is, with a considerable angle between the wing chord and the center line of the fuselage, then they would have an angle of attack appreciably greater than the angle between the center line of the fuselage and the ground. The landing gear could then be made shorter, and from this aspect the solution of the problem

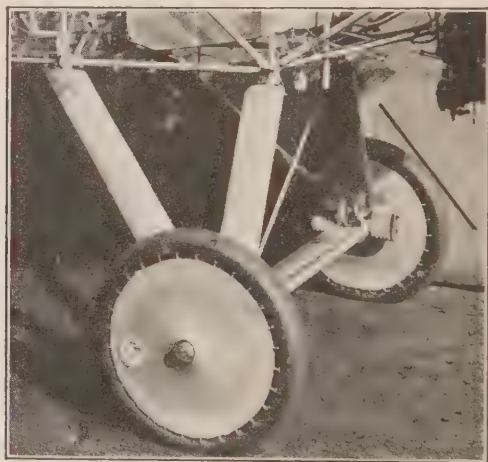


FIG. 48.—Simple landing gear. (*Courtesy Wright Aeronautical Corp.*)

would be a good one; but since when the airplane is at full speed the angle of attack is necessarily small, the fuselage would then point somewhat downward. This would involve an increase in fuselage resistance and would give the airplane an unattractive appearance while in flight.

The tread of the wheels, that is, the distance between them as seen from the front, depends, to a large extent, upon the wing span, for the landing gear should be wide enough so that when the airplane is turned sharply on the ground it will not heel over and allow a wing tip to strike. On the other hand, the tread of the landing gear must not be made too great, for this would involve an increase in weight and air resistance and would also make the

airplane more difficult to steer on the ground. The tread of the landing gear is usually from 15 to 23 per cent of the wing span.

Shock Absorbers.—When an airplane touches the ground in landing, there is naturally some shock, and there must be some means provided in the landing gear to prevent all of it from being transmitted to the rest of the airplane. The tires on the wheels help to absorb the shock, but they are not enough except on the very lightest airplanes. Steel springs might be used, as in an automobile, but these, if used alone, have much

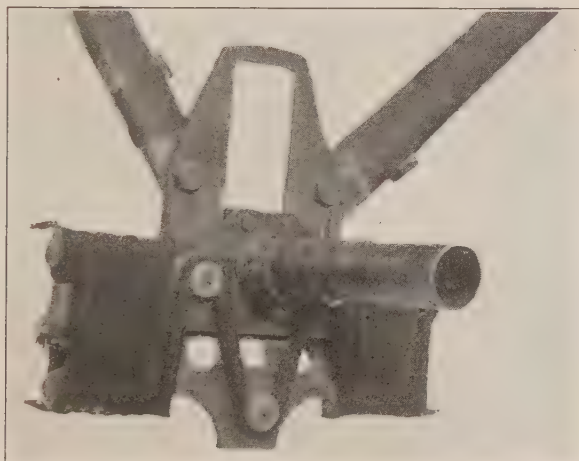


FIG. 49.—Shock absorber using rubber cord. (Courtesy Materiel Division, U. S. Army Air Corps.)

too great a tendency to bounce. It would be possible to supplement them with shock absorbers, but the increased weight and resistance thus involved are usually excessive.

In the past, the device which has been most commonly employed as a shock absorber consists of a rubber cord wound over two spindles, as shown in Fig. 49. One spindle is attached to the axle, and the other to the framework of the landing gear, so that when the wheel strikes the ground and the axle rises, the rubber cord is stretched. The cord itself is not a single piece of rubber but a bundle of small strands inside a fabric cover. For airplanes of moderate size, this cord has an outside diameter of $\frac{1}{2}$ in. and is composed of 275 strands, each about $\frac{1}{26}$ in. square.

The rubber used must be of the best quality, for it may easily be stretched to more than twice its length in an ordinary landing. Government specifications for this material require that it should be capable of stretching to eight times its original length without breaking. As shown in Fig. 49, the axle slides in a guide which is closed at the top, so that the axle cannot come out even if the shock absorber cord should break.

A rubber shock absorber has the distinct advantage of reducing bouncing, for the force required to stretch it is considerably greater than that which it exerts when it is contracting to its normal length. Thus, a large part of the energy of the impact of the airplane against the ground is absorbed in the rubber.

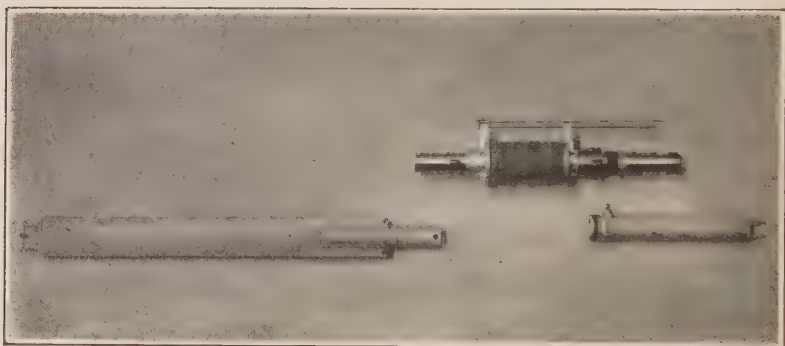


FIG. 50.—Oleo shock absorber. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

Steel springs, on the other hand, give back most of their energy instead of absorbing it and so tend to lift the airplane off the ground again. Rubber has, however, the distinct disadvantage of deterioration with age. This deterioration takes place even when the airplane is not used and ordinarily requires the replacement of the cord once a year.

Because of this difficulty, and the large amount of rubber required for a large airplane, another sort of shock absorber has come into extensive use. This is the *oleo* gear, a typical form of which is shown in Fig. 50. The axle is connected to a piston which slides in an oil-filled cylinder attached to the framework of the landing gear. When the airplane touches the ground, the load on the wheel moves the piston in the cylinder, the oil being

forced through a small hole. In rushing through this hole in the piston, the oil encounters so much resistance as to absorb a large part of the energy of impact. Since the weight of the airplane at rest on the ground would force the piston through the cylinder to the limit of its travel, the shock absorber would be of no benefit when the airplane was taking off, and the gear would not be in a position to absorb any shock until the airplane was in the air and the piston had traveled to the other end of the cylinder under the influence of the weight of the wheel and axle. A spring or rubber buffer is often provided, therefore, behind the piston but is usually stiff enough only to carry the weight of the airplane at rest on the ground. The full travel of the piston is then available to absorb shocks in taking off. This combination of spring and shock absorber differs essentially from that in an automobile, for on the automobile the spring takes all of the direct impact, and the shock absorber merely checks the rebound, while on the airplane most of the direct impact is taken by the shock absorber, and there is little rebound.

Wheels and Tires.—Airplane wheels are usually of the wire-spoke type like those often used on automobiles but are rather lighter in proportion to their strength. They are not ordinarily mounted on roller bearings, because an airplane does too little of its

traveling on the ground to justify the added expense and weight. To reduce the air resistance of the wheels, the spokes are usually covered with a light metal fairing, as shown in Fig. 51.

Tires are of cord construction, like those on automobiles, but much lighter and with much less rubber on the treads. The inner tube is much like that in an automobile but lighter, and air pressures are not much greater than those employed in motor-car practice. Tire sizes vary from 26 by 3 in. for airplanes up to

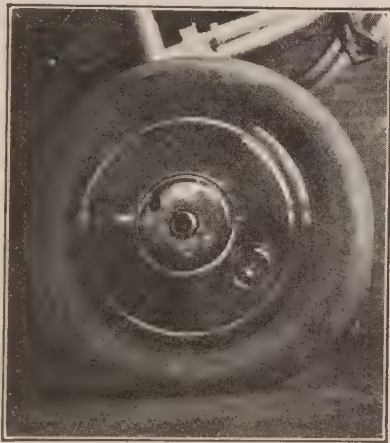


FIG. 51.—Airplane tire, wheel, and fairing. (Courtesy Boston Airport Corp.)

2,000 lb. in weight, to 54 by 12 in. for airplanes weighing 20,000 lb.

Brakes.—If an airplane is to land successfully in a small field, it must stop its run soon after it touches the ground. The resistance of the tail skid dragging over the ground is of considerable use in stopping the airplane, but this is ordinarily not enough, particularly in modern airplanes of low air resistance. It has become quite common, therefore, to fit the wheels of the airplane

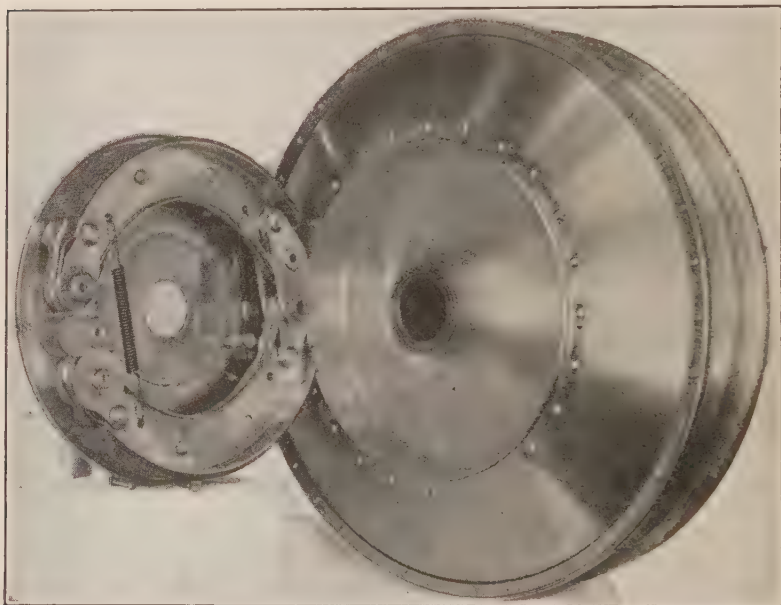


FIG. 52.—Airplane wheel and brake. Brake is removed from wheel to show construction. (Courtesy Bendix Brake Co.)

landing gear with brakes. These are much like those used in automobile practice, except that they are lighter and often are completely enclosed in the wheel so as to offer the least possible air resistance. Frequently, the brake is incorporated in a special disc wheel, as shown in Fig. 52, and the whole assembly is made by one manufacturer.

To assist in steering the airplane on the ground, it is often convenient to be able to apply the brake on only one wheel, or on one wheel more than on the other, so a separate control

for each brake is often provided. These controls may be operated either by hand or by foot. Sometimes they are interconnected with the rudder pedals. Obviously, an airplane brake must be used with caution, because a too sharp application when the tail of the airplane is high may easily result in making the airplane nose over, an accident that almost always results in breaking the propeller, not to mention the possibility of injury to the pilot and passengers. To avoid this danger, the brake controls are sometimes interconnected with the tail skid so that the brake can be applied only when the tail skid is touching the ground. If the brakes are applied too hard, the airplane will start to nose over, but this action lifts the tail skid off the ground and results in an automatic and immediate release of the brake.

Other Landing-gear Arrangements.—The simple arrangement of wheels, axle, and bracing members of a landing gear such as is shown in Fig. 48 is not by any means the only one used. The straight axle may strike an obstacle on the ground and so cause the airplane to nose over. To reduce the danger of such accident by enabling the airplane to straddle an obstacle, the arrangement of bracing shown in Fig. 53 has been widely adopted. This is known as the *split-axle* or *no-axle* landing gear, because the axle is in two parts, each bent up just inside the wheels and terminating at the fuselage or, at any rate, at a point well above the ground. An arrangement of this sort is likely to have somewhat more weight and air resistance than the straight-axle type, but these disadvantages are usually more than offset by the advantage of better ground clearance. The shock absorber may be mounted at the inner side of the wheel, as with a straight axle, but often, particularly when of the oleo type, it is made part of one of the legs of the gear.

On very heavy airplanes, it is frequently impracticable to provide wheels large enough so that each may carry half the load, so that additional wheels are necessary. These extra wheels may be mounted on the same axle with the regular wheels, but often they are carried farther forward. The front wheels then ensure that the airplane will not nose over and thus permit the main wheels to be placed far enough back to reduce materially the load on the tail skid. Figure 54 illustrates a



FIG. 53.—Split-axle landing gear. (Courtesy Bureau of Aeronautics, U. S. Navy, and Chance Vought Corp.)



FIG. 54.—Eight-wheel landing gear. (Courtesy Materiel Division, U. S. Army Air Corps.)

landing gear of this type, on the Barling Bomber, the largest airplane so far constructed in the United States.

Tail Skid.—The tail skid is a support for the rear of the fuselage when the airplane is on the ground. As shown in Fig. 55, it often consists of nothing more than a stick of wood or a length of tubing pivoted at its middle to the bottom of the fuselage, with its upper end attached to some point on the fuselage structure by a length of shock-absorber cord. At the bottom there

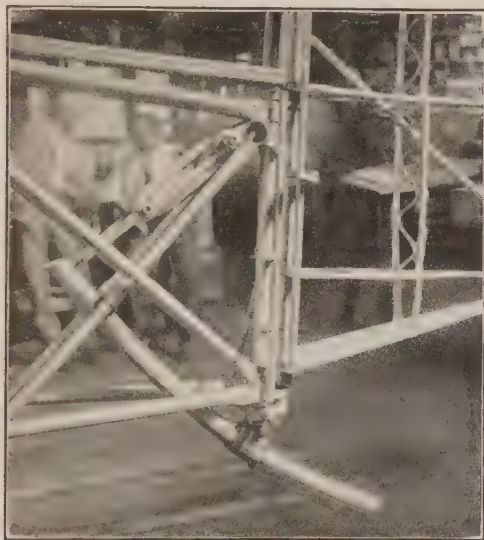


FIG. 55.—Simple tail skid. (*Courtesy Bureau of Aeronautics, U. S. Navy, and Hall-Aluminum Aircraft Corp.*)

is a steel shoe which, as it wears out rapidly in service, is arranged to be easily replaceable. Where more strength is necessary, a tail skid of the tripod type, shown in Fig. 56, is often used. Here the shock absorber is incorporated in the long telescoping member which extends from the shoe to a point at the top of the fuselage.

To make the airplane easier to steer on the ground, the tail skid is often attached to the fuselage by a universal joint so that it can swivel sidewise when the airplane turns. A refinement of this arrangement consists in making the tail skid steerable, so that the pilot has additional control over the airplane on the

ground. Sometimes the tail skid is controlled by a pair of separate pedals within reach of the pilot, but often it is connected directly to the rudder pedals. If this is done, springs are used in the tail-skid control cables, so that if the tail skid happens to jam, the pilot can still operate the rudder.



FIG. 56. —Tripod tail skid. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

Obviously, the end of the tail skid dragging along the ground offers considerable resistance. This is not a serious disadvantage even when the airplane is taking off, because the forward pull of the propeller usually lifts the tail skid clear of the ground before the airplane has run very far. In landing, the resistance of the tail skid may be a distinct help in shortening the run. If the airplane is provided with brakes, however, this additional

resistance is not necessary, so that there is a recent tendency toward substituting a wheel for the tail skid. This wheel is naturally not so large as the main wheels but is of the same type and is fitted with some sort of shock absorber. It may also have a brake. A wheel instead of a tail skid may sometimes be advantageous on soft ground in helping the airplane to get off and also saves the turf on flying fields from being torn up by heavy airplanes.

CHAPTER V

STABILITY AND CONTROL

Stability may be defined broadly as that characteristic of an airplane by virtue of which it flies in a straight path of its own accord. An airplane which does this is said to be stable, and one which does not is unstable. If a stable airplane is momentarily disturbed, as by a side gust of wind, it tends to return of itself to its original attitude; the unstable machine, even if originally in balance, has no such tendency but must be brought back to the original attitude by the pilot.

Control is the action that the pilot takes to make the airplane follow any desired course, and an airplane is said to be controllable when it responds easily and promptly to movements of the control levers.

Stability and controllability do not necessarily go hand in hand. It is quite possible for an airplane to be highly controllable and yet to have little stability. This is sometimes characteristic of military pursuit airplanes, and in the hands of a skilful pilot such an airplane may be distinctly better than a highly stable one. On the other hand, it is quite possible for an airplane to be so stable that it will continue on its own course in spite of all efforts of the pilot to make it do otherwise.

The action of a caster on a piece of furniture rolling along the floor is a convenient illustration of stability in a moving body, for the wheel of the caster tends always to trail directly behind the vertical pivot to which the caster is attached, so that the caster as a whole maintains a constant attitude with respect to the direction of motion. If it were set with the wheel exactly in front of the pivot, it would not maintain this attitude in motion after even the least disturbance but would promptly return to the original attitude with the wheel behind. The caster is, therefore, unstable in every attitude but one.

Since stability and controllability are characteristics of an airplane in motion, it is necessary, before continuing the discus-

sion of these topics, to consider the possible motions of an airplane. At first glance, it might appear that an airplane may move in an infinite variety of ways, but upon closer examination, it develops that there are only six completely independent kinds of motion. Three of these are *linear* motions, and the other three are *angular* motions.

A linear motion is one in a straight line, and when the airplane has only linear motion every part of the machine moves at the same speed, and the directions of motion of all parts of the machine are parallel. The motion of a railroad train on a straight track is an illustration of the simplest sort of linear motion, for while the train can move either forward or back, each of these motions is in the same straight line. The train is then said to have only one possible linear motion. A piece of furniture rolling on a level floor has two possible linear motions, for not only can it go forward or back like the train, but it can also go to the right or left. It can move on either of two lines, each at right angles to the other, such as a north-south line and an east-west line. Motion along a diagonal line, such as northwest, is evidently only the result of a motion to the north combined with one to the west. The north and the west motions are known as *component* motions, while the northwest motion is the *resultant* of the two components. The airplane has the two possible linear motions of the piece of furniture and, also a third one, vertically up or down, that is, the airplane has three possible independent linear motions, and all other linear motions are merely resultants of two or all three of the independent components.

In discussing angular motions, the most convenient example is that of a ship on a rough sea, for the ship can have three angular motions. The first of these angular motions or rotations is a turn to the right or left, during which the ship rotates about a vertical axis. This may or may not be accompanied by linear motion. Usually it is, but it is quite possible to imagine a twin-screw steamer being turned at a standstill by backing on one propeller and going ahead on the other. The other two angular motions of a ship are *roll*, a rotation from side to side about a fore-and-aft axis, and *pitch*, a rotation about a horizontal axis across the ship, so that when the bow is rising the stern is descend-

ing, and *vice versa*. As some unfortunate passengers know only too well, all three of these angular motions may occur simultaneously, but just as any linear motion is the resultant of two or three independent linear components so any angular motion is the resultant of two or three independent angular components. The airplane evidently can pitch and roll just as a ship does. It can, of course, turn to the right or left, also, and this last motion is called *yaw*.

Since the airplane in flight is a free body, that is, one that is not restrained by a track, held down by gravity on a flat surface, or

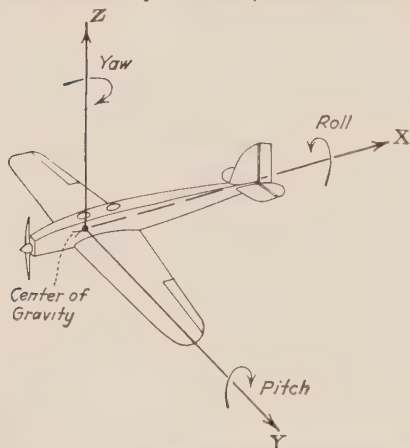


FIG. 57.—Axes, center of gravity, and directions of linear and angular motions.

supported in solid bearings, it will always rotate about its *center of gravity*. This center of gravity is the point at which the airplane could be hung by a single rope and still be perfectly in balance in all directions. It has no actual physical existence, but it is a perfectly definite concept in the mind of the aeronautical engineer and is usually indicated on his drawing of an airplane.

The three mutually perpendicular axes about which angular motion can take place then intersect at the center of gravity, and these lines are also the directions of the three possible linear motions. The axes and the directions of the corresponding motions are shown in Fig. 57.

Longitudinal Stability and Balance.—An airplane is said to possess longitudinal stability when it has a tendency to keep a constant angle of attack with reference to the relative wind, that is, when it does not tend to put its nose down and dive or to lift its nose and stall. Longitudinal stability, therefore, refers to rotation in pitch.

The angle of attack at which the airplane is in equilibrium, and which it tends to maintain constant in flight by virtue of its longitudinal stability, is called the *angle of balance*. Since a

definite airplane speed corresponds to each angle of attack, a certain speed will correspond to the angle at which the airplane balances; this speed is called the *trimming speed*.

It has already been explained that a wing flying alone would be highly unstable in pitch, and it has been stated that a tail surface is necessary on every airplane to overcome this instability of the wing. The action of the tail surfaces in this regard may be explained by referring to the diagram in Fig. 58 (a), which shows an airplane in flight at an ordinary angle of attack. The weight of the airplane is indicated by the arrow marked W , and since the center of gravity is the point about which the airplane would balance if suspended, all the weight may be considered, for the purposes of this discussion, as acting at this point. As already explained in the chapter on the wing, the lift of the wings may also be considered as acting at a single point, the center of pressure, and the arrow marked L_w is, therefore, drawn upward through the center of pressure.

The third important force is the lift on the horizontal tail surfaces, and this is indicated by the arrow marked L_t . Since the center of pressure is behind the center of gravity, it is evident that, were it not for the force on the tail, the airplane would promptly dive. The function of the horizontal tail surfaces at ordinary angles of attack is to supply a down load sufficient to prevent the airplane from diving. The airplane, therefore, balances in the same way in which a lever can be made to balance under the influence of three unequal forces, as shown in the diagram (Fig. 58 (b)). The supporting force on the lever corresponds to the lift on the airplane, and the point of support corresponds to the center of pressure. The large downward force at a small distance from the support on the lever corresponds to the airplane weight. The small downward

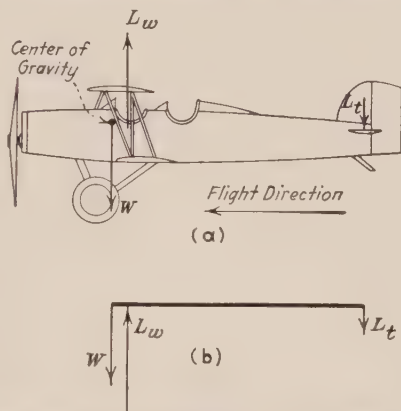


FIG. 58. (a) Equilibrium of airplane in flight. (b) Equilibrium of lever.

force on the end of the lever corresponds to the down load on the tail of the airplane, and the point at which it acts corresponds to the center of pressure of the tail surfaces. It is evident, also, that the lift must be equal to the sum of the weight and the down load on the tail.

The horizontal tail surfaces of an airplane are ordinarily two in number, one fixed and one movable, as shown in Fig. 59.

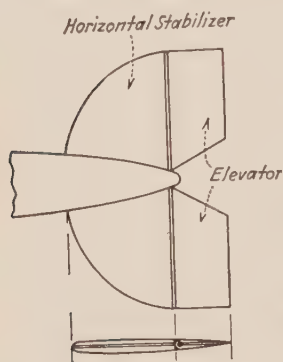


FIG. 59.—Horizontal tail surfaces.

The front one of the two, which is fixed, is called the *horizontal stabilizer* or, often, simply the *stabilizer*. The rear one, which is often divided into two parts, is called the *elevator*. Among pilots, these surfaces are sometimes known as “flippers.” Since only the stability of the airplane is now being discussed, the elevator will be considered for the moment to be fixed, as shown in the diagram, in a position in line with the stabilizer.

From a casual inspection of the horizontal tail surfaces on a conventional airplane, it would probably not be apparent that they carry down load in ordinary flight, for they appear to be set at about the same angle to the longitudinal axis of the airplane as are the wings. The wings, however, are working in undisturbed air, while the tail surfaces are operating in the air which has



FIG. 60.—Effect of downwash on horizontal tail surfaces.

previously passed over the wings. In view of the phenomenon of downwash already discussed, it will be apparent that the air which strikes the tail surfaces has a considerable downward angle with respect to the longitudinal axis of the airplane. This is illustrated in Fig. 60, from which it is evident that the horizon-

tal tail surfaces are really acting at a negative angle of attack with reference to the actual direction of the air which strikes them and that, therefore, they are exerting a downward rather than an upward force.

Suppose, now, that a gust or "bump" causes an airplane which has previously been flying in balance to decrease its angle of attack with reference to its flight path, that is, with reference to the relative wind. As has already been explained, the center of pressure will then move backward, and this movement of the line of action of the lift force will tend to cause the airplane to decrease its angle of attack still more. This action is the instability of the wings in pitch. At the same time, however, the tail surfaces will increase their negative angle of attack, because they are rigidly connected to the fuselage. As a result of this increase, their negative lift will increase, and this increase in downward force at the rear of the fuselage will tend to increase the angle of attack of the airplane as a whole and so to counteract the opposite tendency of the wing lift force. In fact, the increase in down load on the tail of a stable airplane is more than enough to balance the effect of the backward movement of the center of pressure, so that the airplane is brought back to its former angle of attack. If, on the contrary, a momentary disturbance should increase the angle of attack of the wing, then the center of pressure would move forward, and, consequently, the nose of the airplane would tend to rise, increasing the angle still more. Under these conditions, however, the negative angle of attack of the tail surfaces would obviously decrease, and the down load on them would also decrease. In fact, the process might be carried far enough so that the negative angle would be converted to a positive one, and the down load would become an up load. In any event, however, the action of the tail surfaces is again such as to supply a restoring effect more than enough to overbalance the upsetting effect due to the shift in center of pressure on the wing. Once more, therefore, the airplane will be returned to its original angle of attack.

If an airplane has enough longitudinal stability, it will not go into a stall if the engine fails. Suppose the airplane to be flying in a level path in equilibrium and that the engine suddenly stops. The first effect upon the airplane is a decrease in its

forward speed. This leads to a decrease in lift, and with the lift less than the weight the airplane begins to settle, so that the flight path, instead of being level, as before, is inclined downward. Since the direction of the relative wind is always that of the flight path, this means that the relative wind, instead of blowing level at the airplane, is now blowing somewhat upward. The angle of attack is increased, and the stabilizing action of the horizontal tail surfaces comes into play to readjust it to about the same value relative to the flight path which it had before the engine failed. As the flight path now slopes downward, some of the airplane weight acts along it so as to supply a pull which makes up for the loss of propeller thrust. As long as this pull along the flight path is insufficient to compensate completely for the loss of propeller thrust, the airplane will tend to lose speed, but each loss of speed leads to a readjustment to a steeper angle of flight path, and this continues until the airplane is flying at a speed of equilibrium.

The stabilizing action of the horizontal tail surfaces is effective also in correcting the attitude of the airplane to compensate for an increase in engine power. If, while the airplane is flying level and in equilibrium, the throttle is opened wider, the first effect is an increase in airplane speed, and this leads immediately to an increase in the lift to a value greater than the weight of the airplane. The airplane starts to rise, and the relative wind now blows upon it somewhat from above. This decreases the angle of attack, but the action of the tail surfaces is such as immediately to increase it again, so that once more the airplane reaches an angle of equilibrium with respect to a new flight path. This time, however, the flight path is inclined upward.

In the discussions of the three previous paragraphs, no consideration has been given to the action of the slip stream, the blast of air which is driven backward by the propeller. This modifies the lift of the tail surfaces which work in it and so has a distinct effect upon the stability of the airplane. The effect, however, is usually one of degree only, and the statements made above are still true to a fair approximation. The equilibrium speed of the airplane in the glide would, however, be somewhat greater than that in level flight, and that in climb would be slightly less.

Control in Pitch.—So far, it has been assumed that both horizontal tail surfaces of the airplane remain fixed in position relative to the fuselage and that the pilot does not attempt to move them. It is now in order to consider how the pilot employs the controls to change the attitude of the airplane deliberately and so to change its flight path. The combination of stabilizer and elevator is essentially an ordinary airfoil with a flap on the trailing edge. Pulling down the trailing edge of the elevator, therefore, increases the lift coefficient of the combination if the angle of attack is positive, and pulling it up decreases it. When the pilot wishes the airplane to nose down, therefore, he pulls the elevator down, and this decreases the down load on the tail surfaces, so that the rear of the fuselage rises. To make the airplane nose up, that is, to increase the angle of attack of the wings, the elevator is pulled up, the down load on the tail surfaces increases, and the tail is forced down. The lift of the tail surfaces, like that of other airfoils, is proportional to the square of the wind speed, so that if the forward speed of the airplane is reduced, the effectiveness of the tail surfaces in control is, likewise, reduced. This has made it difficult in some airplanes to get the high degree of controllability required for a good landing.

It has already been pointed out that as long as the airplane is flying level, the total lift on all its surfaces must be equal to its weight. The down load on the horizontal tail surfaces evidently varies with elevator angle, but this variation is small compared to the total weight of the airplane, so it is still approximately true that the wing lift in level flight always equals the airplane weight. If, therefore, the pilot wishes to change the angle of the airplane relative to the horizontal and still to maintain it in level flight, he must also change the air speed by opening or closing the throttle.

It has been mentioned previously that the airplane with elevator fixed in line with the stabilizer is balanced at a particular angle of attack and so at a definite trimming speed. If, now, the pilot wishes to fly in a level path at some other speed, he can do so, but to keep the airplane in balance he must change the angle of the elevator. If the speed is to be greater than the trimming speed, the angle of attack must be less than that at which the airplane naturally balances, and to hold this angle in

a stable airplane the elevator must be held down. This results in a lessened down load on the tail surfaces and so causes the airplane to balance again at the new angle of attack, but it will remain in balance only as long as the pilot keeps the elevator down. He may likewise fly in a level path at less than the trimming speed, but in order to do this the angle of attack must be increased. At this increased angle of attack, the airplane if left to itself would again be out of balance, and so this time the pilot pulls up on the elevator and thus applies more down load to the tail.

By use of the elevator, the pilot can compensate also for changes in the center of gravity of the airplane. Thus, if an additional load is placed in the rear of a machine, the elevator can be held down more than would otherwise be necessary, and so an up load is applied to the tail sufficient to restore the balance. On long flights, however, it is tiring for the pilot to have to exert a constant force on the controls to hold the elevator up or down. To overcome this difficulty, and particularly in large airplanes, it is customary to make the stabilizer adjustable. The adjustment is made by a convenient handwheel and permits varying the angle between the stabilizer and the fuselage by 2 or 3° in each direction from the neutral position. In this way, the balance of the airplane can be changed so that it will trim with elevator

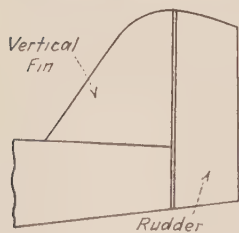


FIG. 61.—Vertical fin and rudder.

neutral at any reasonable speed, and the balance may also be corrected for the effect of changes in the location of the load carried in the airplane.

Directional Stability.—Directional stability in an airplane is the tendency to fly a straight course without yawing to the right or left. It depends chiefly on the two vertical tail surfaces. The front one, which is fixed, is called the *vertical fin* or, often, simply the *fin*. The term *vertical stabilizer* has also been used to designate this surface. To the trailing edge of the fin is attached the other vertical surface, the *rudder*, which is moveable at the will of the pilot. These are shown in Fig. 61. In discussing directional stability, it is assumed that the rudder remains fixed in the same plane as the fin.

In rotations in yaw, the wings have a relatively smaller influence than in the case of rotations in pitch, and this influence is on the side of stability. If the airplane yaws, the wing on the outside of the turn is moving at an airspeed higher than that of the one on the inside. The drag of the outer wing is then greater than that of the other, so that the outer wing is retarded more than the inside one, and there is a tendency for the yawing motion to be checked.

The principal stabilizing action comes, however, from the vertical tail surfaces. When the airplane is pointed directly along its flight path, the vertical tail surfaces are evidently acting at an angle of attack of zero degrees, and exert no force to one side or the other. If the machine yaws, as shown in the diagram (Fig. 62), then a force is set up on the vertical surface of exactly the same sort as the lift on a horizontal surface. In fact, it is called a lift, even though it acts horizontally instead of vertically, because it

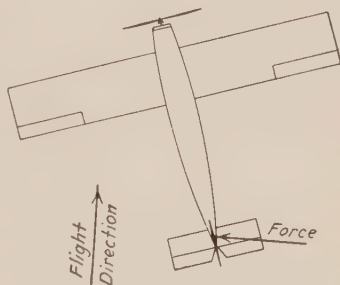


FIG. 62.—Force on vertical tail surfaces in yaw.

comes clearly under the definition of lift as a force at right angles to the direction of the wind. This force on the vertical tail surfaces evidently acts so as to bring the airplane out of the turn which it has started, that is, so as to reduce the angle of yaw, and the action of the vertical tail surfaces is like that of the fin at the back of a weather vane.

Directional Control.—The effect of the rudder is very obvious, since the combination of fin and rudder may also be considered as an airfoil with a flap on the trailing edge. When the rudder is turned, the combination airfoil promptly develops a lift, and a force is set up on the tail of the airplane which tends to turn it. In one respect, the action of the fin and rudder is distinctly different from that of the stabilizer and elevator, for a moderate change in angle of elevator acts simply to change the angle of equilibrium or trimming speed of the airplane, and if the elevator is held in its new position, the airplane soon stops rotating in pitch and reaches equilibrium at a new attitude. If, on the

other hand, the rudder is turned even a little to one side, the airplane will continue to rotate in yaw just as long as the rudder is held over.

Stability and Steadiness.—Stability and steadiness in flight are not necessarily the same thing. If the air is free from irregularities in velocity and direction, then the stable airplane will also be steady, but if the air is rough, then quite the contrary will be the case, for stability is constancy of attitude with respect to the relative wind and not with respect to the ground. If the wind is changeable in direction, the stable airplane will try to head into every gust which strikes it and so will continually alter its attitude with respect to the ground. As this sort of behavior may be distinctly unpleasant for the occupants of the machine, a very high degree of stability is usually undesirable.

Stability in Roll.—While an airplane may pitch without much tendency to roll or to yaw, these last two angular motions are closely related to each other, and under most conditions a rolling rotation leads to a yawing one, and *vice versa*. If, for example, an airplane previously flying in a straight course begins to yaw, the wing on the outside of the turn is, on the whole, moving more swiftly with respect to the wind than that on the inside. On this account, the lift of the outer wing is greater than that of the inner, so that the airplane tends to roll toward the inside of the turn. A certain amount of roll is advantageous, as the airplane needs to bank in a turn to prevent skidding, just as does an automobile on a race track. The difficulty is that the roll continues until the angle of bank has become so great that the airplane begins to slide inward, a motion that is called a *side slip*.

It is possible, however, for an airplane to be designed so as to be stable in this regard, also. Stability in side slip is commonly accomplished by the use of dihedral angle, that is, by sloping the wings upward as they go out from the fuselage. It is quite commonly, but nevertheless erroneously, believed that dihedral acts to limit the angle of roll because the wing which is down, being more nearly horizontal than that which is up, exerts the greater lift. Lift, however, does not necessarily act vertically, so that one wing does not gain in lift over the other by being more nearly horizontal. The true explanation of the action of dihedral

lies in the fact that rolling motion leads to side slip, and the side slip causes the airplane to roll in the opposite direction and so right itself. Let it be assumed that the airplane shown in Fig. 63 has a velocity in side slip as well as a forward velocity. The direction of the relative wind is, then, the resultant of the two component velocities and is diagonally across the wing, as indicated. On the low wing, on the side toward which the machine is slipping, the air first strikes at a point farther out from the center of the airplane than the point at which it leaves the wing; that is, the air travels backward and *inward* across the wing. On the high wing, the path of the air is from a point on the leading edge to one farther out on the trailing edge; the air here travels diagonally backward and *outward*.

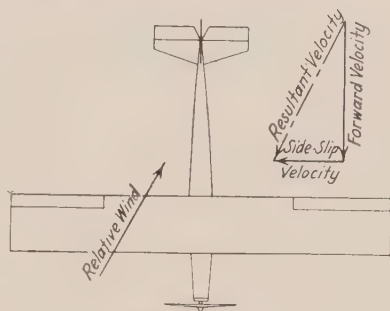


FIG. 63.—Effect of side slip on direction of relative wind.

Since when the machine is on an even keel each wing slopes upward from center to tip, any point on the wing is higher than another point nearer the center. On this account, therefore, the vertical distance between the point on the leading edge where the air first strikes and the corresponding point on the trailing edge

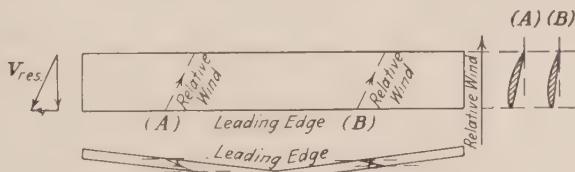


FIG. 64.—Action of dihedral in side slip.

where the same air leaves is greater on the low wing than it is on the high one. This is apparent if a section of each wing is taken in the direction in which the air is actually traveling, as shown in Fig. 64. The shapes of the two sections are alike, though they are not the same as cross sections taken perpendicular to the leading edge. The difference between them lies in the fact

that the leading edge of the section from the low wing is at a considerably greater distance above the trailing edge than is that of the section from the high wing. This means, in effect, that the true angle of attack of the low wing is greater than that of the high one; and since the low wing has the greater angle of attack, it is obvious that it will also have the greater lift and will tend to rise. It must be emphasized again that this stabilizing action due to dihedral occurs only when there is side slip. Without side slip, the dihedral has little if any effect upon the characteristics of the airplane in roll, and an airplane with a moderate amount of dihedral can be rolled just as easily as one without it.

It is possible, however, for an airplane to have too much dihedral, and this is particularly true of military airplanes and of others that ought to be capable of being side slipped deliberately as a means of landing in a small field or for some other purpose. For this reason, the angle of dihedral is seldom greater than 3° and is more often only $1\frac{1}{2}$ or 2° .

Since side slip follows excessive roll, it is evident that yaw may also result from it, for as the airplane rolls and begins to slip in the direction of the low wing, the resultant relative wind will strike on one side of the vertical tail surfaces. This sets up a force at right angles to the wind direction which tends to turn the airplane in the direction of the side slip, a tendency that the pilot may check by giving opposite rudder.

Control in Roll.—To control the rolling motion of the airplane, the ailerons are provided. These are flaps on the trailing edges of the wings near the tips and are interconnected in such a way that when the aileron on one side turns down, that on the other turns up. Pulling down an aileron increases the lift of the wing on that side of the airplane, and pulling the other up decreases the lift on the other side, so that the airplane rolls accordingly. The ailerons, therefore, enable the pilot to check any rolling motion in straight flight before it has gone far enough for side slip to begin. In turning, he may use the ailerons to make the airplane bank sooner than it would under the action of the yawing motion alone, and he may use them after the correct angle of bank is reached to prevent it from increasing.

The ailerons are usually quite satisfactory for controlling the rolling motion of the airplane at ordinary angles of attack.

When the airplane is flying at or near the stalling angle, however, other factors enter into the situation that may cause the action of the ailerons to be very inadequate. To remedy these difficulties many devices have been tried. A combination of an aileron with a Handley Page slot appears to be of material benefit, but controls of this sort have not yet come into common use, and space does not permit describing them in detail.

Control Operating Mechanism.—A typical airplane control system is shown diagrammatically in Fig. 65. The rudder is is

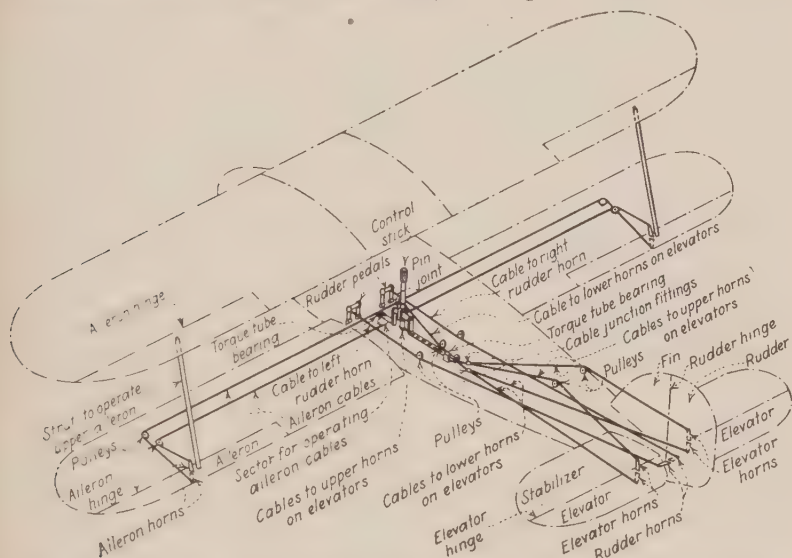


FIG. 65.—Airplane surface-control system. (Courtesy Wright Aeronautical Corp.)

operated by the pilot's feet, either with a rudder bar or by means of pedals. The rudder bar is the simpler arrangement, but pedals have the advantage of requiring less width in the fuselage and of easier adjustment to suit pilots of different height. From the rudder bar or pedals, two cables lead back to short masts or *horns*, one on each side of the rudder. Since the cable from the left side of the rudder bar, or from the left pedal, as the case may be, leads to the horn on the left side of the rudder, it is apparent that when the pilot pushes with his left foot, the trailing edge of the rudder will move toward the left and the airplane will turn

to the left. This action, it should be noted, is the opposite of that of the corresponding control on a bicycle or a bobsled.

The control cables from the horns on the elevator and from those on the ailerons are connected to a moveable vertical member called the *control stick* in the pilot's cockpit. The stick is supported at the bottom by something equivalent to a universal joint, so that the top of the stick can be moved in any direction. The control cables from the elevator are connected to the stick,



FIG. 66.—Wheel-and-post control. (Courtesy Materiel Division, U. S. Army Air Corps.)

as shown, in such a way that pushing the top forward causes the trailing edge of the elevator to move down and so tends to make the airplane dive. Conversely, pulling the stick back causes the nose of the airplane to rise, so that, in either case, the airplane rotates in the same direction as the stick. This requires that the cables from the elevator to the stick be crossed; the cable from the lower horn of the elevator is connected to a point on the stick above the pivot, while that from the upper horn is connected to one below. The same effect is often obtained by

leading the cable from the upper horn over a pulley in front of the stick and then back to the same point at which the other cable is attached.

The cables from the horns on the ailerons are led to the stick in such a way that moving the top of the stick to the right causes the trailing edge of the aileron on that side to rise, so that the airplane rolls in the same direction in which the stick is rotated. In large airplanes, it is difficult to give enough movement of the ailerons by means of a control stick without requiring excessive effort on the part of the pilot. In these airplanes, therefore, the ailerons are often controlled by a wheel mounted on the top of the stick, as shown in Fig. 66. The arrangement of the controls is then such that turning the wheel to the right makes the airplane roll to the right, and *vice versa*.

While the relations between control movements and corresponding airplane movements are the same in all machines, the mechanical details of control mechanisms vary so widely that it is out of the question to attempt to discuss them at length.

CHAPTER VI

THE AIRPLANE ENGINE

GENERAL PRINCIPLES

The engine is truly the heart of the airplane. Like the engines of other vehicles, it furnishes the means for moving from place to place, but, unlike them, it also provides the power necessary for support. When the engine ceases to function, the airplane must come to earth in a very short time.

Requirements.—The requirements that the airplane imposes on its engine are many and include not only extremely light weight in proportion to the power developed but also the ability to run without failure for long periods of time, at high power, and with the lowest possible consumption of a generally available fuel. These and other special requirements will be more fully discussed in the next chapter. Suffice it to say here that the only type of engine which has thus far been able to meet the demands of the airplane successfully is the internal-combustion gasoline engine. It is the purpose of this chapter to point out the fundamental principles of operation of this type of engine. These are the same whether the engine is used in airplanes or automobiles or for other purposes.

Definition of Engine.—An engine is a machine for converting the heat energy derived from burning a fuel into mechanical work, such as rotating a shaft, which, in turn, can be made to do useful work such as driving the wheels of an automobile or rotating an airplane propeller. The term "internal combustion" refers to the fact that the fuel is burned within the engine itself, thus eliminating the furnace and boiler which are necessary for the steam engine.

Combustion.—The process of burning, or *combustion*, requires both fuel and air. Of these two, air is required in much the larger quantity. In order to burn a gallon of gasoline, about 90 lb. of air are necessary. This amount of air, at sea level,

occupies a volume of 1,200 cu. ft. The gasoline engine, therefore, must be designed primarily to handle air, the volume of gasoline being insignificant when compared with the volume of air that must go with it. Thus it happens that a gasoline engine bears a close resemblance to an air pump, built strongly enough to withstand the high pressures and temperatures developed by combustion.

The Engine as an Air Pump.—The maximum power which an engine can develop depends on the *weight* of air that it can pump, since fuel can be burned and heat energy developed only in proportion to the weight of air available to unite with that fuel in the process of combustion. There is nothing gained by supplying more fuel than can unite with the air present, since the excess of fuel will merely be wasted. The conception of the engine as an air pump is fundamental to a good understanding of the principles of the internal-combustion engine.

The *weight of air* that an engine can pump depends primarily on the density of the air (that is, the weight of a given volume), the size and number of engine cylinders, and the speed of the crankshaft. With a given air density, therefore, the maximum power which an engine can develop depends primarily on the number and size of its cylinders and the revolutions per minute of its crankshaft. For example, of two similar engines, each having the same size and number of cylinders, the one that can run at the higher speed should be able to develop the higher power. Of two similar engines running at the same speed, the one having the larger cylinders will develop the higher power. In each case, the increase in power is due to the fact that more air is pumped in a given time and more fuel can, therefore, be burned and the heat converted into work.

Elements of the Engine.—The essential elements of a gasoline engine are shown by Fig. 67. The *cylinder* is a short tube, open at one end, and closed by the *cylinder head* at the other end. The *piston* is a cup-shaped member, arranged to slide back and forth within the cylinder which fits around it closely. Leakage past the piston is prevented by the *piston rings*, which are carried in grooves in the piston and press tightly against the inner walls of the cylinder. The *piston pin* passes through the piston and through the end of the *connecting rod* the opposite end of which is

bored to receive the *crankpin*. Rotation of the *crankshaft* moves the piston up and down in the cylinder, and pressure on the piston, when applied at the proper time, will rotate the crankshaft. The crankshaft is enclosed in the *crankcase* which also supports the cylinder and most of the other parts of the engine. In the cylinder head are mounted the *intake valve* and the *exhaust valve*.

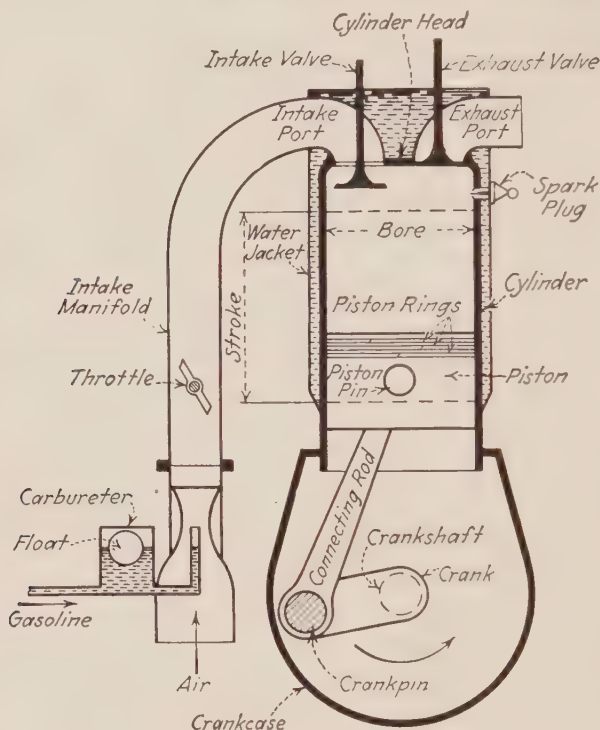


Fig. 67.—Principal elements of a gasoline engine.

Sometimes, there are two intake and two exhaust valves, but this does not alter the principles of operation.

The valves control the opening from the *intake port* to the cylinder and from the cylinder to the *exhaust port*, respectively. They are operated by a mechanism driven from the crankshaft, which will be described later. The intake port is connected by a passage, called the *intake manifold*, to the *carbureter*. The exhaust port may be open to the air or connected to an *exhaust*

manifold, or a *muffler*, though the latter is rare in airplane practice. Screwed into the cylinder, close to the top, is a *spark plug*, connected by a wire to a source of electric current.

Definitions.—The diameter of the inside of the cylinder is called the *bore*, the distance through which the piston moves from one extreme to the other is called the *stroke*, and the area of the top of the piston in square inches multiplied by the length of the stroke in inches, multiplied by the number of cylinders, is called the *piston displacement* of the engine. The extreme upper position of the piston is called the *top center*; and the extreme lower position, the *bottom center*. The space in the cylinder above the piston at top center is called the *compression space* or *combustion chamber*; and its volume, the *compression volume*.

Cycle of Operation.—The way in which the gasoline engine operates is illustrated by the diagrams in Fig. 68. At *a*, the piston is shown near the top-center position of the *intake* or *suction* stroke. As the crankshaft is revolved by the starter or by the other cylinders or by the flywheel after the engine has started, the intake valve opens and the downward motion of the piston draws into the cylinder air with which is mixed, by means of the carbureter, the proper amount of gasoline vapor. When the piston reaches bottom center, the cylinder is filled completely with this mixture, and the intake valve is closed. The piston then moves back toward the cylinder head on the *compression* stroke, as shown at *b*. The purpose of the compression stroke is to compress the mixture of air and gasoline vapor into a smaller space, thus increasing its pressure and temperature. It has been found that much more power is developed by the engine if the mixture is compressed than if it were simply burned at atmospheric pressure. Near the top of the compression stroke, an electric spark is caused to jump between the points of the spark plug, the mixture is ignited, and the fuel vapor combines with the air very suddenly in the process of combustion. This sudden burning of the fuel generates a very high temperature and pressure in the cylinder, and the piston is driven down with great force on the *power* stroke, shown at *c*. The energy delivered to the piston on this stroke furnishes power to turn the crankshaft through all the other strokes, with enough left over to do useful work. Near the end of the power stroke the exhaust valve opens,

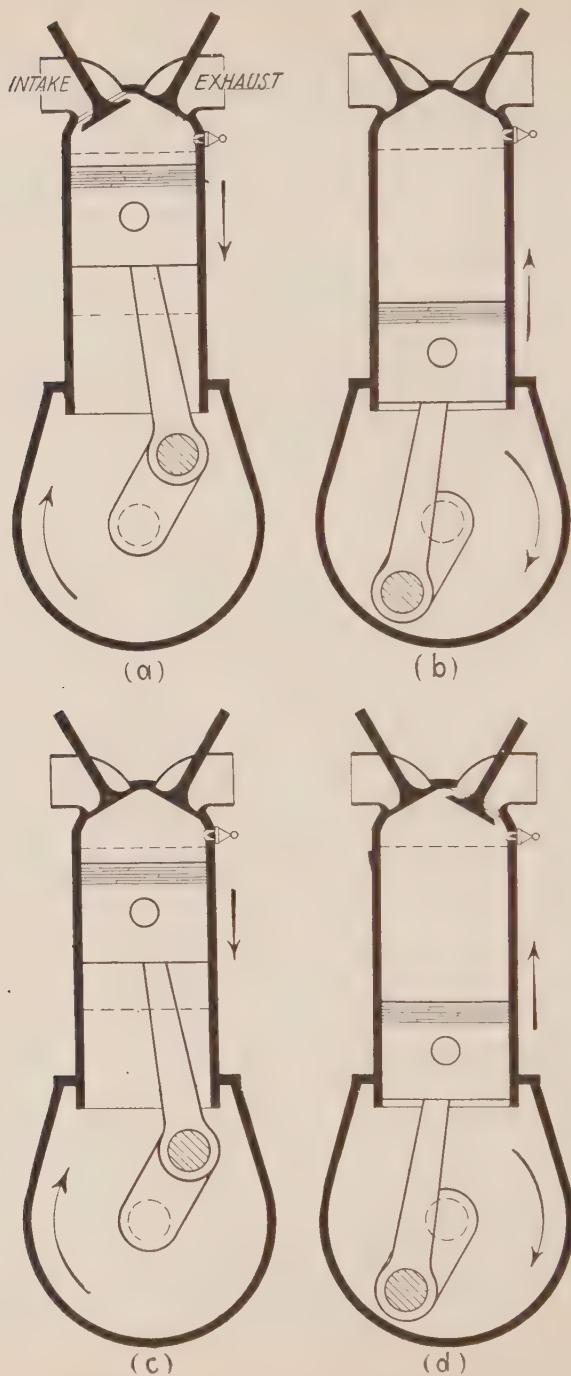


FIG. 68.—Positions of the four-stroke cycle.

allowing the burned gases to escape, and as the piston moves toward the cylinder head on the *exhaust* stroke *d* most of the remaining burned gases are pushed out through the exhaust valve and the cylinder is ready for the inlet stroke again.

Two- and Four-stroke Cycles.—It should be noted that there are four distinct strokes of the piston, two toward and two away from the cylinder head, only one of which is a power-producing stroke. The other strokes are used in drawing in and preparing the mixture for combustion or in getting rid of it after it has burned, so that a fresh mixture can take its place. From this it is evident that the gasoline engine is not self-starting, since it cannot produce a power stroke until the crankshaft is rotated to give the intake and compression strokes. Since four strokes are required to complete the sequence or *cycle* of operations, engines operating in this way are said to operate on the *four-stroke cycle* and are often called *four-cycle* engines. The *two-stroke cycle* is not used in airplane engines at the present time. It is essentially the same as the four-stroke cycle except that the intake and exhaust processes are performed with the aid of a separate pump and there are only two strokes in the cycle of operation of the working cylinder.

Pressures and Temperatures.—The pressures and temperatures which occur within the cylinder during the compression and power strokes are very high. In the airplane engine running at full power, the maximum pressure at the time of combustion may be 600 lb. to the square inch or more, with a maximum temperature in the neighborhood of 4400°F. Average values for the temperatures and pressures are shown in Fig. 69, which is an *indicator diagram* from an airplane engine at full power. This diagram is a graph showing the pressures within the cylinder for various positions of the piston during the four strokes of the cycle previously described.

Losses.—No heat engine converts all of the heat energy in the fuel into the form of useful work at the crankshaft. By referring to the indicator diagram, we see that the temperature at the time of exhaust is very high, which means that much heat is wasted when the exhaust gases are discharged to the atmosphere. There is, also, a large loss in the form of heat given up to the cylinder walls and piston, which must be taken care of by the

cooling system. Certain chemical and physical losses also are present, and considerable work is lost in overcoming friction. It has been found that the portion of the total heat of combustion which is turned into useful work depends, to a great extent, upon the *compression ratio*. The compression ratio is defined as the ratio of the total cylinder volume with the piston at bottom center to the volume of the compression space. The higher this ratio the larger proportion of the heat energy of combustion will

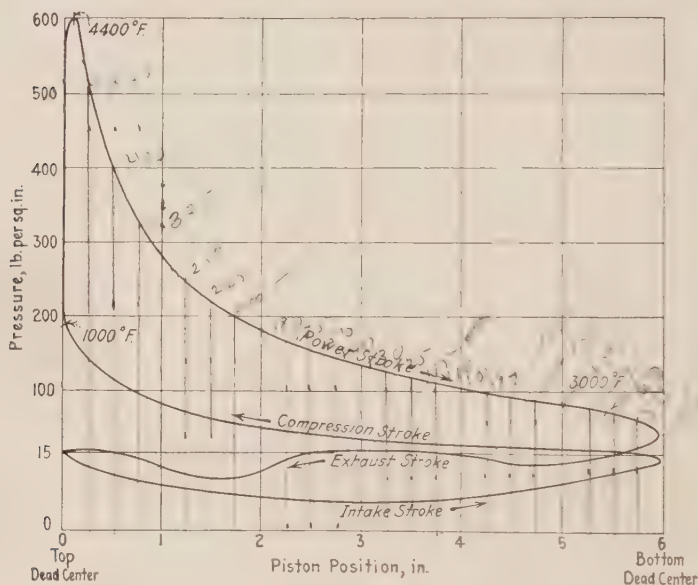


FIG. 69.—Typical indicator diagram.

be turned into useful work at the crankshaft, other things being equal. It is thus desirable to use the highest practicable compression ratio.

Detonation.—If gasoline vapor and air are compressed beyond a certain point, the combustion that takes place after the spark has ignited the mixture takes a very undesirable form. The speed of combustion increases so rapidly that the process becomes a very violent explosion which causes abnormally high pressures within the cylinder. This condition can be recognised by a sharp metallic “knock” or ringing sound, often heard in the case of an

automobile engine when it is "pulling" very hard at low speed. Since it is impossible to run with severe knocking, or *detonation*, for any great length of time, the highest compression ratio which can be used must be slightly lower than that at which severe detonation occurs. It has been found that different fuels act differently in regard to detonation, some knocking at low compression ratios, while others do not knock at all. Ordinary gasoline cannot be used with a compression ratio over 5, while with aviation gasoline, the maximum allowable compression ratio under aircraft-engine conditions is about $5\frac{1}{2}$.

Efficiency.—With a compression ratio of $5\frac{1}{2}$, the well-designed airplane engine, running at full power, will convert about 25 per cent of the heat energy of the fuel into useful work at the crankshaft. This means that the losses previously mentioned amount to 75 per cent of the total heat energy in the fuel and that the *efficiency* is 25 per cent. This may seem small, but it compares very favorably with that of other types of engines. For instance, the efficiency of the ordinary steam locomotive is about 5 per cent, that of the steam-driven ocean vessel about 15 per cent, while large electric generating stations just about equal the 25 per cent efficiency achieved by the airplane engine. With most fuels other than gasoline, the compression ratio, and, hence, the efficiency, may be increased, but no such fuels are as yet commercially available at a reasonable cost. It appears that airplane engines will use gasoline for some time to come.

Antiknock Compounds.—The tendency of gasoline to detonate can be reduced by mixing with it certain chemicals called *antiknock compounds*. A chemical known as tetraethyl lead, now sold in gasoline for motor-car use, is most effective in this respect but is very expensive and cannot be used in sufficient quantity to effect any very great increase in the compression ratio without seriously increasing the cost of the fuel. It is quite possible, however, that with increased production this or some other antiknock compound may be produced at much lower cost and may be generally available. When this condition is brought about, it will be feasible to increase the compression ratio of gasoline engines considerably and thus obtain a higher percentage of useful work from a given amount of fuel, that is, a higher *efficiency*.

Spark Advance.—An important consideration in the gasoline engine is the point at which the spark occurs with relation to the top-center position of the piston. Although the process of combustion is extremely rapid, an appreciable amount of time is consumed between the passage of the spark and the attainment of maximum pressure in the cylinder. In order that the maximum pressure shall occur near the beginning of the power stroke, it is necessary that the passage of the spark be timed to occur somewhat before the top-center position of the piston. The number of degrees of crankshaft rotation between the occurrence of the spark and the top-center position of the piston is called the *spark advance*. The amount of spark advance necessary depends chiefly on the engine design, the speed of the crankshaft, and the degree of throttle opening. It is possible to provide an automatic mechanism which will give somewhere near the proper amount of spark advance under these various conditions, but, for airplane engines, sufficiently good results can be obtained by setting the spark to give best operation at full speed and full power. It is usually necessary to *retard* the spark to about the top-center position when starting the engine.

Cooling.—Referring again to Fig. 69, one is impressed at once by the very high temperatures that exist during the greater part of the cycle of operation. With the gases in the cylinders at such temperatures, it is quite evident that a great deal of heat will be transmitted to the engine parts in contact with the gases and that, unless some provision is made to carry away this heat, the cylinder, piston, and valves will attain very high temperatures. In order to prevent these parts from becoming too hot, it is necessary to take away the heat as rapidly as it is received from the hot gases. This is the function of the *cooling system*.

Air Cooling.—There are two distinct methods of cooling the cylinders of an internal combustion engine. The first and simpler is called *air cooling*. Air is blown against the cylinders in such a way, and at such a velocity, that it will take away heat from the outside of the cylinder and cylinder head as rapidly as heat is received from the hot gases. The surface of a cylinder does not present sufficient area for this purpose, and in order to be able to cool the cylinder with a reasonable air speed, thin projections, or *fins*, are added to the cylinder all over its outer

surface. These provide a much greater total area in contact with the cooling air than in the case of a smooth cylinder, and through their use the cylinder can be satisfactorily cooled by air alone.

Water Cooling.—Another method of cooling is to provide a *water jacket*, or space around the cylinder and cylinder head which can be filled with water, as shown in Fig. 67. This space is kept full during engine operation, and the water is circulated by means of a pump through a device known as a *radiator*. The radiator is an assembly of small tubes or flat metal passages through which the water is allowed to flow. The outside surface of these passages is exposed to a blast of air, and the water passing through them is thus cooled. After passing through the radiator, the water is circulated back to the engine where it again receives heat and is pumped back to the radiator to be re-cooled. It is evident that even with "water" cooling, air is really the cooling medium. In the case of the water-cooling system, the water simply acts as an intermediate vehicle between the cylinder walls and the air.

Carbureter.—A very important feature of all gasoline engines is the *carbureter*. This is the device which mixes the fuel with the air as the latter flows to the cylinders. Among those not thoroughly acquainted with the internal-combustion engine, the carbureter is often considered to be a mysterious and complicated piece of mechanism, responsible in a large measure for all the ills and ailments to which such engines are subject. In reality, the carbureter is a simple mechanism which seldom fails to function satisfactorily. Figure 70 shows a carbureter in its simplest form. It consists essentially of a main air passage through which the engine draws its supply of air. Near the middle of this passage is a restriction or *venturi*, the purpose of which is to increase the velocity of air at the point where the fuel is introduced. Fuel is introduced through the *nozzle* whose outlet is at the smallest diameter of the venturi. In the upper end of the air passage is the *throttle valve*. The throttle valve shown in the illustration is called a *butterfly* throttle and is the type commonly used. It is simply a disc, mounted on a shaft so that it can be turned in the passage to close it off completely or to allow any desired degree of opening from the carbureter to

the engine. The throttle is the main engine control, since it regulates the amount of air and fuel mixture received by the engine. The accelerator pedal of an automobile or the throttle lever in an airplane are connected to the throttle valve. The fuel nozzle receives its supply of fuel from the *float chamber* which carries the *float*. The purpose of the float is to maintain a constant level of gasoline in the float chamber. For this pur-

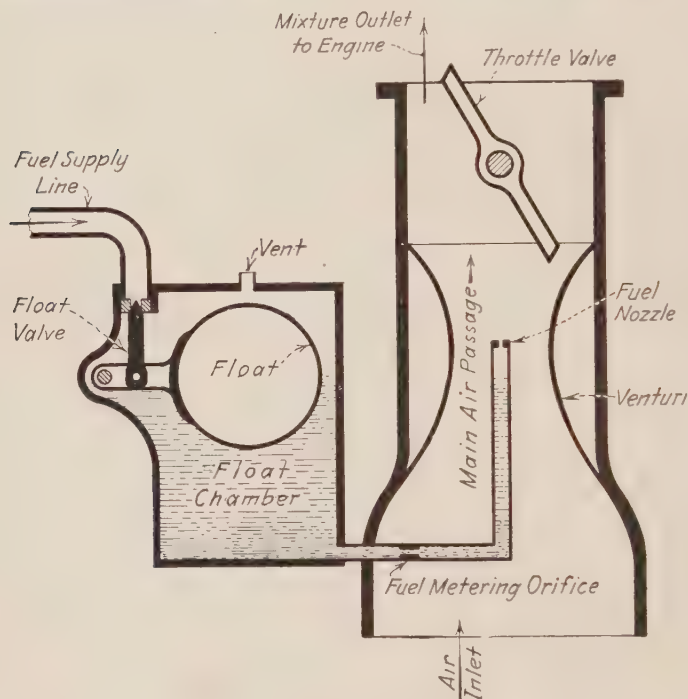


FIG. 70.—Simple carbureter.

pose, it is connected to a *float valve* which controls the supply of fuel from the fuel tank. The fuel-supply line from the tank is shown in the figure. The top of the float chamber must be connected by a small passage, or *vent*, to the atmosphere or to some part of the carbureter which is essentially at atmospheric pressure.

Carbureter Action.—The action of the carbureter is as follows: The engine draws air through the venturi past the fuel nozzle,

and the suction so created draws gasoline from the nozzle. The fuel leaves the nozzle in the form of a fine spray, which is carried along with the air and mixes with it. A large part of the gasoline actually *evaporates* into the air during its passage through the intake manifold, but there is usually some gasoline left in the form of liquid when the mixture enters the cylinder. Heat from the cylinder walls, from the piston, and from the exhaust gases remaining in the cylinder evaporates such liquid gasoline, so that all of the fuel is in true vapor form before ignition occurs. Fuel in the liquid form will not burn (when liquid gasoline "burns," it is only the vapor coming off the liquid which is consumed). The reason that engines sometimes do not start when cold is that there is not enough heat in the engine parts to evaporate enough gasoline to allow combustion to take place.

If the fuel-metering orifice (Fig. 70) is of the proper size, the proportion of fuel to air will remain approximately constant, except when the flow of air is very slow, no matter how much air is being drawn through the carbureter. The actual carbureter carries additional parts, not shown in the diagram, to secure the proper ratio of fuel to air at very low speeds of the engine, when the flow of air is slow. Other passages and devices are necessary to give the proper mixture ratio for a sudden *acceleration* or increase in speed of the engine, but the main part of most carbureters is the simple arrangement illustrated.

Distribution.—The mixture of fuel and air is *distributed* to the various cylinders supplied by one carbureter by means of the intake manifold. Such manifold consists of a branched pipe or passage which connects the carbureter with the several intake ports. The manifold must be so designed that it will convey, as nearly as possible, the same amount of air and fuel to each cylinder. When this is accomplished, the distribution is said to be good. It is relatively easy to distribute equal amounts of air, and if all of the fuel is in vapor form, the air will carry with it equal amounts of fuel to the various cylinders. If, as is usually the case, there is liquid fuel present in the manifold, equal distribution of this is very difficult, as it tends to adhere to the walls of the manifold and flow to certain cylinders more than to others. In automobile practice, this difficulty is overcome by heating the intake manifold by means of the exhaust gases, so

that most of the fuel is evaporated in the manifold. Since this method reduces the power of an engine considerably, airplane engines usually use a "lighter," that is, a more *volatile*, grade of gasoline which evaporates more completely and can, therefore, be distributed to the cylinders in approximately equal amounts without heating the intake manifold.

Ignition System.—The essential parts of the ignition system are shown diagrammatically in Fig. 71. There are two separate

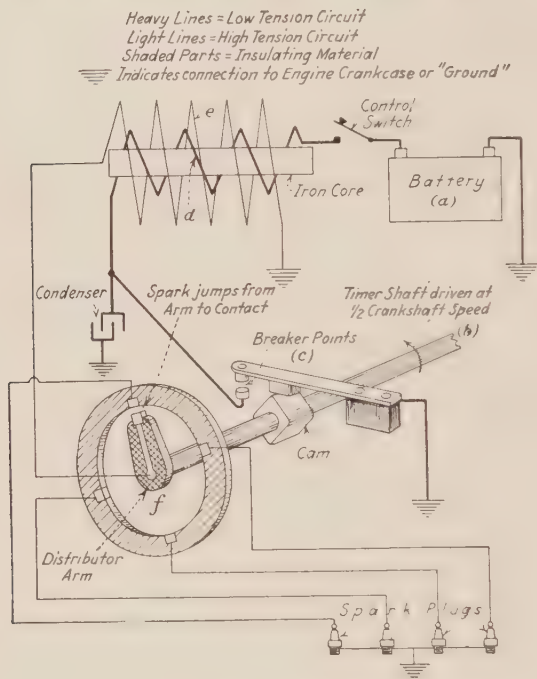


FIG. 71.—Circuit diagram of battery-ignition system.

circuits in such a system, the *low-tension circuit* (shown with heavy lines) and the *high-tension circuit*. In the low-tension circuit is a source of electric current *a* which may be a battery or the armature of a small generator, called a *magneto*. A shaft *b*, driven by some part of the engine, operates an *interrupter*, or *breaker*, *c*, which controls the current through the low-tension coil *d*. This coil consists of a number of turns of insulated copper

wire wound around an iron *core*. Surrounding the low-tension coil is a high-tension coil *e* consisting of a very large number of turns of fine wire, and this is connected through a *distributor f*, driven by the engine at half crankshaft speed, to the various *spark plugs*. When the interrupter breaks the low-tension circuit, the sudden change in magnetism in the core induces a high voltage in the secondary coil. This is carried through the distributor to one of the spark plugs and causes a spark to jump between its points. The distributor and breaker must be so *timed* that the spark occurs in the proper cylinder at the proper time with respect to the position of the piston on the compression stroke.

Spark Plugs.—A cross-section of a typical airplane-engine spark plug is shown in Fig. 72. It consists essentially of a steel shell *a* which contains an insulator *b* made of mica or porcelain. Through the center of this insulator is an electrode *c* on the top of which is a connection *e* for the high-tension wire from the ignition system. The inner end of the electrode *c* terminates within the cylinder at a short distance from another electrode *d* which is connected to the shell of the spark plug.

The function of the spark plug is to insulate the electrode *c* from the electrode *d* so that when the ignition system supplies current to the connection *e* the spark will be forced to jump between the points inside the cylinder. The spark plug must be so designed that it will run at the proper temperature. If this temperature is too high, the electrode points get red hot and cause the mixture to ignite before the proper time, a phenomenon known as *preignition*. If the spark plug runs too cold, carbon and oil will accumulate on the points and eventually *short circuit* them. This causes the familiar trouble known as *spark plug fouling*. Special types of spark plugs are necessary for aviation engines, since they are subject to very high temperatures for long periods of time.

Valve Gear.—A typical mechanism used to operate the valves of a gasoline engine is shown by Fig. 73. The names of the

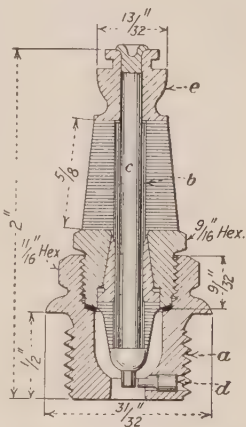


FIG. 72.—Cross-section of airplane spark plug. (Courtesy B. G. Corp.)

various parts are given on the diagram. The principal operating member is called a *cam*, and consists of a circular steel disc with a projection, or *lobe*. The cam is mounted on the *camshaft*, which is revolved at one-half the crankshaft speed by means of the *timing gears*. The valve is opened when the lobe of the cam pushes up the *follower*, the motion of which is transmitted through the *push rod* to the *rocker arm*, which opens the valve. As the

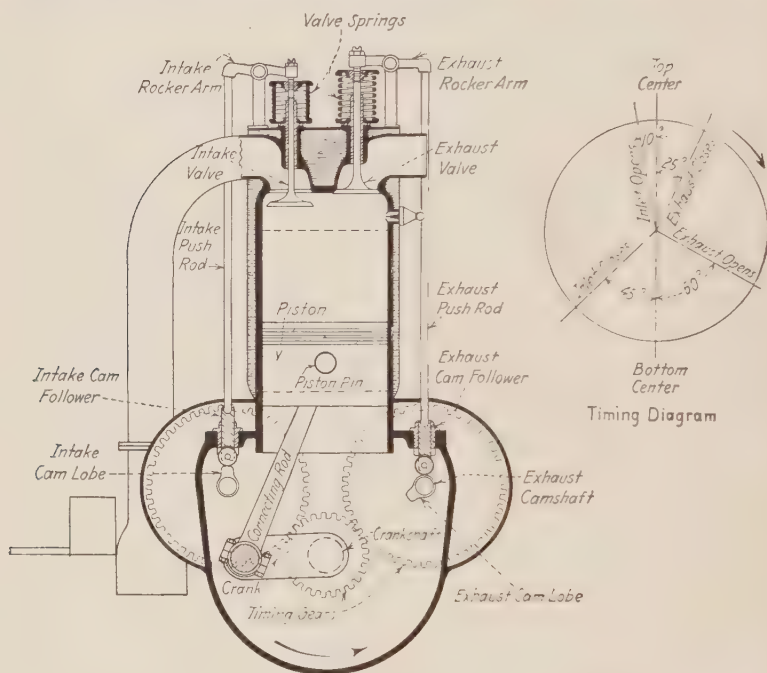


FIG. 73.—Valve-operating mechanism and timing diagram.

lobe of the cam leaves the follower, the valve is closed by the *valve spring*. Since each valve is required to open once during every 2 revolutions of the crankshaft, it is evident that the camshaft must run at half crankshaft speed. In some engines, a cam carries more than one lobe, in which case the speed of the camshaft must be correspondingly reduced. Sometimes, the camshaft is carried along the top of the cylinders, and the cams act directly on the rocker arms or followers. This is called an *overhead camshaft*.

The *timing*, or relation of the opening and closing of the valves with respect to the piston position, is very important. A typical timing of the valves measured in degrees of crank rotation with respect to the top and bottom center positions of the piston is given in Fig. 73.

Lubrication.—In order that the various moving parts of the engine may work smoothly together, *lubrication* by oil is necessary. Oil is supplied to the various bearings, usually by means of a small pump driven from the crankshaft of the engine. The oil from this pump is led through passages into drilled holes in the crankshaft. In passing into the crankshaft, the oil lubricates the main crankshaft bearings. From there it is conveyed through the crankshaft to the crankpin bearings and, after passing through the crankpin bearings, is thrown out in the form of a spray on the cylinder walls, pistons, and piston pins. Oil from the pump may be forced through holes drilled in the camshaft and from there be thrown out over the valve mechanism. It is necessary that auxiliary shafts and gears be lubricated, and this is usually done by means of additional pipes or passages from the oil pump. After lubricating the various parts of the engine, the oil falls into the bottom of the crankcase and is recirculated. The oil supply may be stored in the crankcase itself, or there may be an external tank so arranged that the pump can draw oil from the tank. In the latter case, *scavenging pumps* return the oil from the crankcase to the tank after it has passed through the engine. The outside-tank arrangement is known as the *dry-sump* system, while storage of the oil in the crankcase is called the *wet-sump* system of lubrication.

CHAPTER VII

THE AIRPLANE ENGINE (*Continued*)

PERFORMANCE, TYPES, DETAILS

In the previous chapter, the general principles of the internal-combustion gasoline engine were discussed, without extensive reference to its use in the airplane. In adapting the engine to airplane requirements, certain features become of great importance, and these will now be discussed in some detail.

DEFINITIONS

Before proceeding further, it may be well to define specifically some of the more common terms used in airplane-engine work.

Horsepower.—The term horsepower as used in engineering has very little relation to the power developed by a horse. It is defined as the power necessary to lift a load of 33,000 lb. through a height of 1 ft. in 1 min. A large horse can do this amount of work for a short time but cannot keep it up continuously. A man can develop only about $\frac{1}{10}$ hp. for any extended period of time.

Maximum Power.—The maximum power or *full throttle* power of an engine is the highest power that it can develop at normal speed. When the term "engine power" is used, maximum power is meant unless otherwise indicated.

Rated Power.—The *rated* power of an engine is the power output at normal speed which is guaranteed by the manufacturer. It is usually somewhat less than the maximum power.

Engine Speed.—Unless otherwise noted, engine speed will be referred to as the number of revolutions per minute of the crankshaft.

Normal Speed.—The *normal speed* of an airplane engine is the speed at which it is designed to run when developing rated power.

Weight.—The weight of an airplane engine is usually taken as its weight complete with carbureters and ignition system but without accessories, propeller, fuel, oil, or water.

Front of Engine.—Since most airplane engines are used to drive tractor propellers, the propeller end of the engine will be referred to as the *front* of the engine. The left and right sides of an engine will be considered as viewed from the pilot's seat in a tractor airplane.

ENGINE REQUIREMENTS

In order to be satisfactory for airplane use, an engine must be able to develop the necessary power with the least possible weight and bulk, must drive its propeller at a suitable speed, must consume as little fuel as possible in a given time, must be very "flexible" in operation, and must perform these functions unfailingly and without undue vibration over long periods of continuous running. It must have these qualities not only under test conditions but also under all normal conditions of flight, at various altitudes, and in various airplane maneuvers. It is further expected that such an engine will be reasonable in first cost and be capable of being maintained and operated with a minimum of time and expense, by non-technically-trained men.

Weight.—A complete airplane can weigh, with engine and load, not more than 30 lb. for each horsepower developed by its engine at full throttle. If the airplane is to be safe and is to have a satisfactory speed and rate of climb, the total weight per horsepower must be much less than this. For high-speed military pursuit airplanes, for instance, 1 hp. is required for every 6 to 7 lb. of weight of the entire machine with load. ¹¹ The ratio of total airplane weight to the rated power of the engine is called the *power loading* of the airplane. Tables V and VI (pp. 262 and 279) give power loadings for various kinds of airplanes.

It is evident that the weight per horsepower of the engine must be a great deal less than the power loading of the airplane, so that a considerable portion of the power loading may remain to provide for the airplane structure, the engine auxiliaries, and the load to be carried. The internal-combustion engine is the only engine which has so far been able to meet satisfactorily this weight requirement. In fact, mechanical flight in a heavier-than-air machine would hardly have been possible before this type of engine was developed.

Light weight in the airplane engine is achieved by details of design and arrangement that will be described later and by using the highest practicable crankshaft speed. The final weight per horsepower developed depends not only upon these factors but also upon the size of the engine. Small engines weigh more in proportion to the power that they develop than large engines, since the small engine carries almost as much in the way of pumps, magnetos, carbureters, etc., as the large engine. Also, the minimum thickness of material which can be used is limited to a certain definite value by manufacturing considerations. It is, therefore, only to be expected that engines of small output will weigh more per horsepower than engines of large output. The weight of the modern airplane engine varies from about $3\frac{1}{2}$ lb. per horsepower for small commercial engines to $1\frac{1}{2}$ lb. per horsepower for large military engines. Engines forced to extremely high outputs for racing purposes have been made to weigh slightly less than 1 lb. per horsepower.

Engine Speed.—It was pointed out in the previous chapter that the power that can be developed by an engine depends on the amount of air it can pump and that an increase in power may be obtained either by increasing the size of the engine or by increasing the crankshaft speed. Since an increase in size involves a corresponding increase in weight, while speed can be increased with very little additional weight, the airplane engine must be capable of running at relatively high speeds. The maximum speed at which such an engine can run is usually limited by the speed for good propeller efficiency. This varies from 1,600 to 2,500 r.p.m., depending on the airplane speed. Sometimes the propeller shaft is geared to run at a speed lower than that of the crankshaft, in which case the engine can be allowed to run at a speed somewhat faster. Geared airplane engines run at normal speeds of 2,000 to 3,000 r.p.m. In this case, the speed is limited by considerations of engine durability or valve capacity, or both.

POWER REQUIRED AND POWER AVAILABLE

As has been already noted, the maximum output of an engine is approximately proportional to its speed. An airplane propeller on the other hand, has a quite different characteristic. The

power that it requires is proportional, approximately, to the cube of its rotational speed. If we plot curves, against rotational speed, of the maximum power available from the engine, and the power required by a propeller, a graph is produced as shown in Fig. 74. It will be noted that the two curves cross at a certain point, which is the speed at which the engine will turn the propeller if the throttle is wide open. The size of the propeller is selected so that this will be the normal speed of the engine in level flight. Since the propeller absorbs the maximum engine power at this point only, it is not possible to operate the engine propeller unit at any lower speed than this without closing the throttle. When the throttle is closed, the power output is reduced along the curve of power required by the propeller.

Propeller Load.—The curve of power required by the propeller, plotted against engine speed, is called a *propeller-load* curve. Strictly speaking, it varies somewhat with the speed of advance of the airplane, but for a given airplane, propeller, and engine, this variation is small and may be neglected in a brief consideration of engine performance.

FUEL CONSUMPTION

Low fuel consumption in an airplane engine is chiefly desirable from the point of view of reducing the weight of fuel to be carried, but it is also important, especially in commercial flying, for keeping the cost of operation as low as possible. The amount of fuel which an engine consumes in a certain time depends on its efficiency and the amount of power which it is developing. It is obviously impossible to compare the fuel consumption of two engines of different size on the basis of total fuel consumed in a given time. The larger engine will usually consume more fuel than the smaller one. It is, therefore, customary to consider the fuel consumption of an engine in relation to the power which it is developing. Fuel consumption is, therefore, measured in "pounds of fuel per horsepower per hour,"⁴ and this is called the *specific fuel consumption*. Figure 74 shows the specific fuel consumption of a typical airplane engine during both full-throttle and propeller-load operation. It will be noted that, on the propeller load, the specific fuel consumption increases rapidly

as the speed is reduced. The principal reason for this is that when the power of an engine is reduced by throttling, an increasing proportion of the power goes into overcoming friction in the engine bearings and pistons, and less power remains for useful work at the propeller. Aviation engines at maximum power use in the neighborhood of $1\frac{1}{2}$ lb. of gasoline per brake horsepower per hour. If a well-designed airplane engine uses much more than

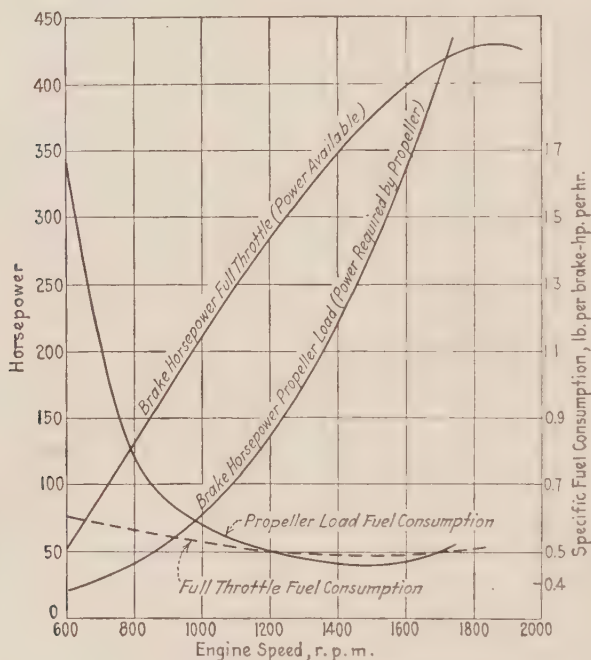


FIG. 74.—Power and fuel consumption.

this amount of fuel at full throttle, it is usually due to the fact that the carbureter is supplying more fuel than is necessary to utilize all the air being pumped into the engine and the excess fuel thus supplied is being wasted out of the exhaust. Airplane engines having very high compression ratios and using special fuels or antiknock compounds may have specific fuel consumptions at full throttle as low as 0.42 lb. per brake horsepower-hour.

Oil Consumption.—The same principles apply to oil-consumption as to fuel-consumption requirements. Since the amount

of oil consumed by a gasoline engine is small as compared with its fuel consumption, the oil to be carried never forms a very appreciable portion of the power-plant weight. A specific oil consumption of from 0.01 to 0.05 lb. per horsepower per hour is allowable in airplane-engine practice. Excessively high oil consumption usually indicates some fault in engine design or adjustment and is likely to cause spark-plug fouling.

Weight of Fuel and Oil.—The importance of low fuel and oil consumption in reducing the weight to be carried by an airplane

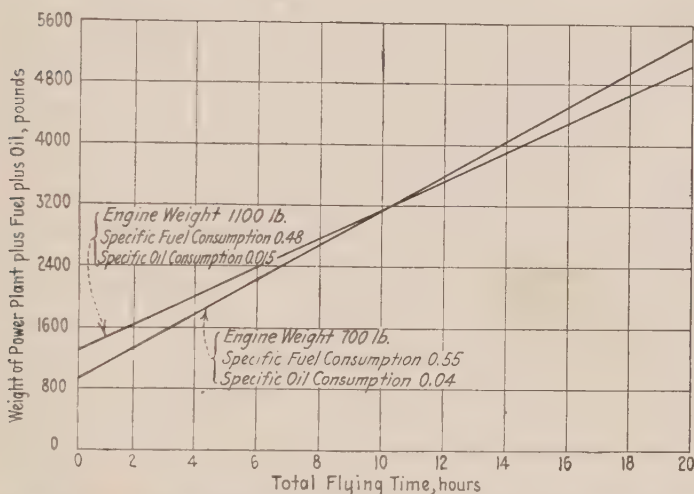


FIG. 75.—Weights of two 400-hp. engines with fuel and oil for flights of various durations.

is emphasized by Fig. 75. This is a graph showing the total weight of engine, fuel, and oil to be carried for flights of different durations. Two curves are shown, one for each of two engines, which develop the same power. One engine is much lighter than the other but has a higher specific fuel and oil consumption. It will be seen at once that for flights of short duration, the light engine gives a lower total weight, regardless of the fact that it is not economical in the use of fuel and oil, while for longer flights the heavier but more economical engine gives less total weight to be carried.

ALTITUDE PERFORMANCE

In order to understand the effect of altitude on engine performance, it is necessary to recall again that the amount of power that an engine may develop is dependent on its capacity as an air pump. In the previous chapter, it was pointed out that the maximum power output of an engine depended on the size and number of its cylinders, the crankshaft speed, and the density

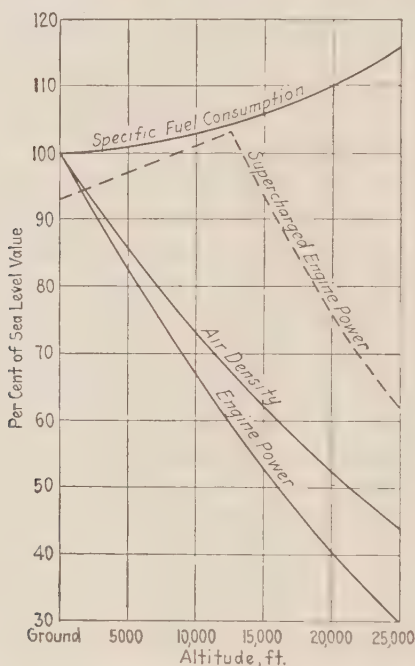


FIG. 76.—Variation of air density, engine power, and specific fuel consumption with altitude.

of the air. The size and number of the cylinders obviously remain constant, irrespective of altitude, and it has been found that the speed of the crankshaft remains approximately constant with altitude at any given throttle position. We know, however, that the density of the air decreases very rapidly with altitude. It is, therefore, to be expected that the power output of an engine will decrease approximately in proportion to the air density, and this is actually the case. Figure 76 shows the average power of

an airplane engine at various altitudes, based on its sea-level horsepower. The decrease in power with altitude causes a reduction in airplane speed and climb, but since the decreased density of the air decreases the drag of the airplane, the reduction in airplane speed with increasing altitude is not so great as the reduction in engine power.

Fuel Consumption.—As the altitude of an engine is increased, the specific fuel consumption is somewhat increased, owing to the fact that the over-all efficiency of the engine is reduced as the air density decreases. The average increase of specific fuel consumption with altitude is shown in Fig. 76. In computing the performance of an airplane at various altitudes, the changes in power and in specific fuel consumption must be taken into consideration.

Supercharging.—There is a method by which the reduction of power with altitude can be largely offset, and this is by an apparatus known as a *supercharger*. The supercharger is an air pump driven by the engine, the purpose of which is to compress air to sea-level density and deliver it to the engine. This enables the engine to pump the same weight of air as it would at sea level. When using a supercharger, therefore, the power output of an engine will remain approximately constant, until the altitude is reached above which the supercharger is no longer capable of delivering air at sea-level density. Above this altitude, the power will decrease at the same rate as if the engine were not supercharged. The highest altitude at which a supercharger will maintain sea-level density at the carbureter is called the *critical altitude* of the supercharger. Typical superchargers are described in Chap. IX.

Performance in the Air.—The power and fuel-consumption curves (Fig. 74) and the altitude-performance curves (Fig. 76) are the results of laboratory tests. It must be realized that tests of this kind are made with the engine in good condition and with all adjustments correctly made. Unfortunately, this is not always the case when the engine is in use in an airplane. It is more difficult to make and maintain correct adjustment in the airplane, and, of course, the condition of the engine deteriorates somewhat with extended use. Furthermore, the average pilot is not so experienced in operating engines as the personnel of the

laboratory. For all these reasons, it is to be expected that the performance of an engine in flight under service conditions will not be so good as that shown by laboratory curves. Some allowance for this must be made in designing airplanes and in computing airplane performance. It is probable, however, that these differences are not very great and that the performance of an engine under service conditions is seldom inferior to the laboratory performance by more than 5 per cent.

RELIABILITY

We have placed the desirability of light weight and adequate performance first, for without these particular characteristics it is obvious that the airplane engine cannot fly at all. Assuming, however, that these characteristics are present in a sufficient degree, there is no question that the next most important factor is reliability. The necessity for reliability in airplane engines is obvious, because failure of the power plant means an immediate "forced" landing.

Design.—Reliability is achieved first of all by the most careful design. Each part of a new engine design is considered in detail, and many calculations are made as to its strength and ability to function properly. Reliability is greatly assisted by simplicity, and the designer always tries to use as few parts as possible and make these of relatively simple shape. Certain special features can be used to promote reliability. For instance, every bolt and nut on an airplane engine must be carefully secured by a wire or *cotter pin*, to make sure that it cannot possibly come loose during flight. Duplicate ignition systems are generally used. A large number of cylinders promotes reliability, for if one or two cylinders should fail, the engine might still deliver enough power to continue in flight.

Testing.—Even the most experienced designers are not infallible, so that it is necessary to test a new type of engine by many hours of full-throttle running on the ground, before it is used in an airplane or approved for production. The government requires that a new type of engine shall run without serious failure at least 50 hours at or above rated power, before it will be approved. In addition to the government tests, most manu-

facturers submit their engines to further endurance tests at full throttle to make sure that they are reliable. After an airplane engine is placed in production, a most careful inspection system is maintained at the factory, to make sure that only the correct materials are used, and that every part is made strictly in accordance with drawings and specifications. Every engine, even though of an approved type, is given severe tests at the factory before it is delivered for installation in an airplane.

Multiengined Airplanes.—Another way of increasing power-plant reliability is to use two or more small engines in place of one large one. A discussion of this method will be found in Chap. XIV.

Operation.—In spite of the most careful design and testing on the part of the manufacturer, the reliability of an airplane engine depends, to a great extent, upon the care used by the operator to keep it in good condition. Experienced mechanics should carefully inspect the engine before and after every flight, and it should be disassembled for inspection and overhaul at reasonable intervals. Most modern airplane engines will run for about 300 hours of ordinary flying before such overhaul is necessary. The pilot also has a great deal to do with the reliability of his engine. He should run it at full throttle no longer than is absolutely necessary. A careful pilot can run even a mediocre engine in such a way that failure is very unlikely. Perhaps most important of all, however, is that the airplane designer should choose an engine sufficiently large so that the airplane can be operated most of the time with the engine at less than maximum power. Running an engine considerably below its maximum power will do more than anything else to promote reliability.

MANEUVERS

The airplane engine is called upon to operate in maneuvers and "stunts" where the airplane assumes a great many different angles with respect to the earth. In this way, it differs from the automobile and stationary engine, which normally operate in somewhere near a horizontal position. The metal parts of the engine are not affected by changing positions, but the fuel and oil supply are affected greatly, and provision must be made to

take care of this condition. This involves special features of design in the carbureter and lubrication system that are not necessary in other types of engines.

OTHER REQUIREMENTS

Compactness.—Since space is always limited in the airplane, it is essential that the airplane engine occupy a space as small as possible in proportion to its power. The size of the engine as viewed from the front is especially important, since, in many cases, this determines, more than any other factor, the size and head resistance of the fuselage. Where engines are located outside the fuselage, a small frontal area is even more desirable. The number and arrangement of the cylinders chiefly determines the degree of compactness and the amount of frontal area of an engine in proportion to its size.

Vibration.—Another quality especially important for airplane engines is comparative freedom from vibration. The airplane structure is light and, therefore, somewhat flexible, and an engine with severe vibration would, in many cases, gradually break down the structure. Even when the airplane structure is not affected, a vibrating engine is likely to cause breakage of the pipes and wires which connect the engine to its various auxiliary systems. This, of course, cannot be allowed, since failure of an auxiliary system is usually just as serious as breakage of the engine itself. The need for comparative freedom from vibration is usually met, in the case of the airplane engine, by using a comparatively large number of cylinders arranged so as to balance each other, as will be explained later.

Flexibility.—By flexibility is meant the ability of an engine to run smoothly at all speeds from the lowest, or *idling*, speed, to its maximum speed. In addition to this, it must be able to *accelerate*, or increase its speed, and *decelerate*, or reduce its speed, quickly and surely in response to movements of the throttle. The gasoline engine is quite satisfactory in this respect, if provided with properly designed carbureters and manifolds. A low engine speed is necessary in gliding and especially in landing and taxiing. The idling speed is generally about 200 r.p.m. when the airplane is at rest on the ground.

Maintenance and Repair.—Since the airplane engine runs a great deal of the time at or near its full power, it is likely to need considerable inspection, maintenance, and repair work, and it is especially desirable that the engine be so arranged that this work is made relatively easy. Certain parts and auxiliaries should be accessible even when the engine is installed in an airplane, and the engine should be so designed that assembly and disassembly are facilitated. The arrangement of the cylinders and the location of the various auxiliaries and accessories has a decided influence on maintenance. Easy maintenance not only reduces operating costs but also allows an engine to be used a greater portion of the time than one which must be “laid up” for repairs for long periods.

Cost.—It is because of the extreme importance of the qualities previously mentioned that the item of cost of the airplane engine has been put last. It is, of course, desirable that the airplane engine be as cheap to build as possible, but the other desirable characteristics must not be sacrificed for this purpose, and, therefore, the airplane engine is relatively expensive as compared with some other types. The need for light weight and reliability requires the use of expensive materials and complicated machining processes, and this involves additional expense over types of engines where these qualities are not important. The present cost of airplane engines, which is in the neighborhood of \$15 to \$20 per rated horsepower, is somewhat higher than will be the case when airplane engines are built in larger quantities.

ENGINE CONSTRUCTION

Materials.—The materials used in the construction of airplane engines consist largely of aluminum alloys and special alloy steels. In general, the crankshaft, camshaft, connecting rods, auxiliary shafts, gears, valves, valve-gear parts, and linings of the cylinders are made of alloy steel, while the crankcase, cylinder heads, pistons, and housings for the auxiliary drives are made of aluminum alloys. Such alloys are usually *cast*, that is, made by pouring the molten metal into moulds where it cools and hardens in the shape of the mould. A forged aluminum alloy, often called *duralumin*, is sometimes used for the main crankcase and for gears which are not too heavily loaded. Pumps, car-

bureters, etc., are usually made of aluminum castings, with bronze or steel moving parts. Bolts and nuts are of the best alloy steel. Piston rings are of cast iron or steel. Where ball or roller bearings are used, these are made of special alloy steel, with a very hard surface. Plain bearings for steel shafts are made of bronze or *babbitt* metal. Babbitt is an alloy consisting largely of tin and copper, is rather soft, and forms an excellent bearing material for crankshafts and connecting rods.

Cylinder Construction.—There are, in general, two different types of cylinder construction used in aircraft engines. The first type, used on both water- and air-cooled engines, consists of a steel cylindrical portion, or *barrel* in which the piston slides. Steel or iron is necessary for the cylinder barrel, for if a softer material, such as aluminum, were used, the piston and piston rings would wear out the cylinder too rapidly. The cylinder head, and sometimes the *jacket*, which extends down over the barrel, are made of cast aluminum alloy. Since this is not hard enough to withstand the impact of the valves, bronze valve seats are inserted. The cylinder of the Wright Whirlwind engine is of this type. In the second type of cylinder, used in water-cooled engines only, the cylinder is built up entirely of thin steel parts welded together, and the whole is surrounded by a sheet-steel water jacket welded in place. The water-cooled Liberty-engine cylinder is a good example of this type of construction.

Valves.—Exhaust valves are subjected not only to a severe “hammering” from the valve gear but also to the extremely high temperatures of the exhaust gases which pass out around the valves. This causes exhaust valves to run at extremely high temperatures, sometimes even at “red heat.” In the early days of airplane engines, exhaust valves would last only a short time, but improvements in design and material have gradually overcome most of this trouble. Exhaust valves of modern engines are fairly well cooled, and special alloy steels are used which will retain their strength and hardness even at very high temperatures.

ENGINE COOLING

Air Cooling.—Air-cooled engines must be equipped with *fins* on their cylinders, as previously explained. In addition to this, the cylinders must be exposed to a stream of air at high

velocity. In the airplane engine, this stream of air is usually supplied by the propeller and by the motion of the airplane through the air. The cylinders, therefore, must be so arranged that air can reach each one in adequate quantities and flow over its entire surface. In order to accomplish this, the cylinders are separate, one from another, with spaces between them. Air passages formed of sheet metal may be used to assist in distributing the cooling air over the cylinders.

For a long time, air-cooled engines were not looked upon with favor, since many of the early designs were unreliable and gave low power and high fuel consumption as compared with water-cooled engines. In recent years, however, air-cooled engines have been improved to such an extent that many types are available whose performance and reliability are equal to those of the best water-cooled engines.

Water Cooling.—Water-cooled engines must be supplied not only with water jackets surrounding the cylinders and cylinder heads but also with a pump to circulate the water and with the necessary piping to carry the water from the pump to the cylinder jackets and from the jackets to the radiator. The water pump is usually of the centrifugal type, driven through gearing from the crankshaft. The pump shaft is generally made of a rustproof material, such as bronze or stainless steel, with aluminum-alloy castings for the housing and the impeller.

Lubrication.—Aircraft engines are lubricated by oil supplied to the bearings under pressure. A small pump driven by the crankshaft is used for this purpose. This pump is usually in the form of a pair of spur gears which receive the oil between their teeth and carry it around to the discharge side of the pump. The pressure of the oil, which is usually between 50 and 100 lb. per square inch, is regulated by a small spring-loaded valve. The oil system includes pipes and passages to carry the oil to the various bearings and a fine screen or strainer to remove grit and other foreign matter. After lubricating the various engine parts, the oil falls into the crankcase where it is removed by another set of pumps called the *scavenging* pumps and delivered back to the oil-storage tank. Most airplane engines depend on an external tank for their oil supply, though the crankcase forms the supply tank in some small models. Oil is continually drawn

from this tank, forced through the strainers, and the bearings, and returned to the tank. A certain amount of oil escapes past the piston rings into the cylinders. Much of this oil is blown out the exhaust valves, but some always burns, or partially burns and forms carbon. The engine is said to "consume" all oil which escapes past the piston or leaks out at other places.

Carbureters.—Aircraft carbureters operate on the general principles outlined in the preceding chapter, but their arrangement and mechanical detail vary considerably. The aircraft

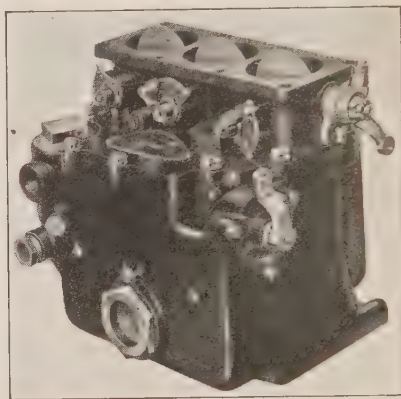


FIG. 77.—Carbureter for Wright Whirlwind engine. (*Courtesy Stromberg Motor Devices Co.*)

carbureter is designed to be as light and compact as possible, and to this end several carbureters are often combined into one casting. The carbureter of the Wright Whirlwind (Fig. 77), for instance, is, in reality, three separate carbureters combined in one casting with a common float chamber. This saves considerable weight and complication over three separate carbureters and allows the three throttles to be mounted on a single shaft controlled by a single lever. For V engines, the carbureters are usually combined in pairs, and each pair is supplied by a single float chamber. In American practice, these carbureters are usually located inside the V of the engine, but in British and European practice they are usually outside the V. The Napier Lion (Fig. 94, p. 129) is an example of foreign practice in carbureter location. A large three-barrel carbureter is mounted

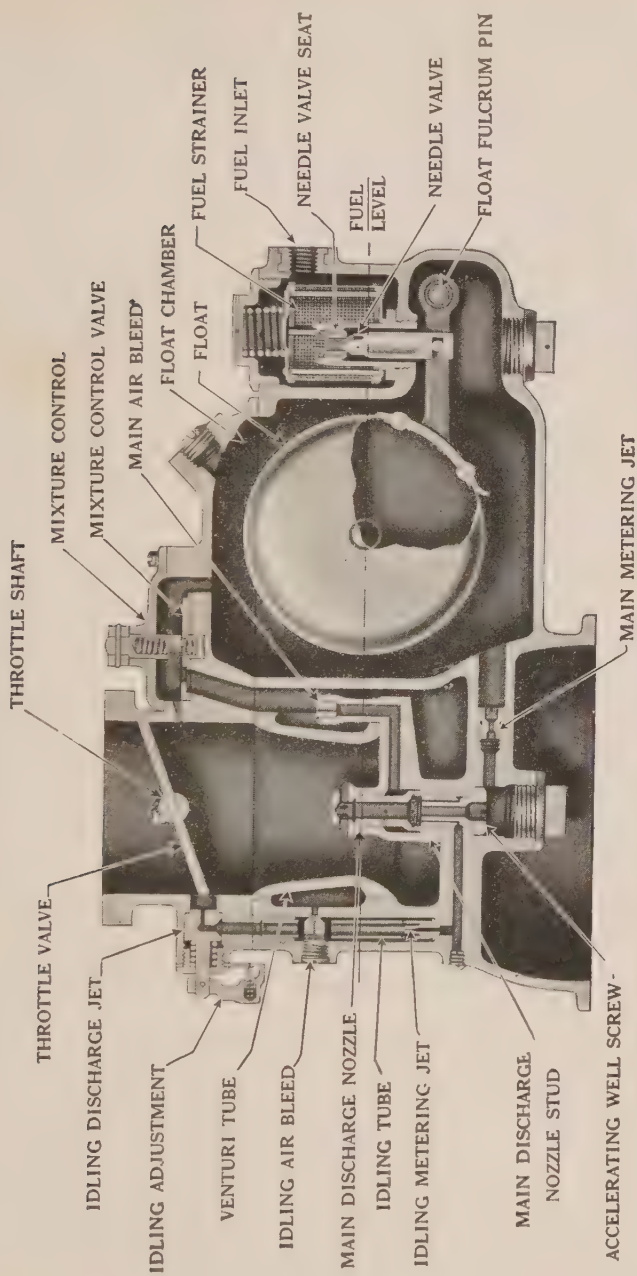


Fig. 78.—Cross-section of typical airplane carburetor. (Courtesy Stromberg Motor Devices Co.)

at the rear of the engine and is connected by a short pipe to the rear of each cylinder bank. A passage, cast in each of the three cylinder head castings, conveys the mixture to the intake ports. A study of the other engine pictures will show the location of the carbureters and their general arrangement. Figure 78 shows the interior construction of a typical aircraft carbureter. The additions to the simple carbureter described in the previous chapter are for the purpose of securing good idling and acceleration, for compensating for altitude, and for making the carbureter operate in the various positions that an airplane engine is called upon to assume during maneuvers.

IGNITION SYSTEMS

As pointed out in the previous chapter, provision must be made to furnish a spark to each spark plug at the proper time in each cylinder. This is accomplished either by a small high-



FIG. 79.—Airplane type magneto. (Courtesy Scintilla Magneto Co.)

voltage generator known as a *magneto* (Fig. 79) or by a storage battery connected to the low-tension coil. A storage battery will run down very rapidly unless it is constantly charged, so that a *generator* is also necessary in a battery system.

The chief advantage of the magneto is that no battery is required, and this system is used in airplanes which do not require

lights and other electrical apparatus. On airplanes requiring lights, radio, etc., it is necessary to carry a generator and storage battery. In this case, it would seem logical to omit the magnetos and to supply the energy necessary for ignition from the generator and battery. Some engine designers, however, prefer to use magneto ignition even in this case, so that the engine will be entirely independent of any other electrical system used on the airplane and will continue to run even if the battery system supplying the lights, etc., should fail. The magnetos or other ignition apparatus are usually located at the rear of the engine. There are some exceptions to this, however, as will be seen from the engine photographs. The modern ignition system for the aircraft engine has been developed to a very high stage of reliability, but it is still considered advisable to carry two separate ignition systems, each firing one of the two spark plugs in a cylinder. This is now universal practice in all but the smallest aircraft engines.

PROPELLER REDUCTION GEARS

Since the desirable speed for an airplane propeller is usually less than the maximum permissible crankshaft speed of the engine, reduction gearing between the crankshaft and propeller is sometimes used. Such an arrangement allows the engine to run at a higher speed, therefore developing more power than an ungeared engine with the same propeller speed. Many of the engines listed in tables III and IV can be supplied with reduction gears if so ordered. The Napier Lion and Rolls-Royce Condor are geared, except sometimes for racing purposes. Since the propeller reduction gear receives the entire power output of the engine and must, at the same time, be very light, it must be very carefully designed and be made from the best possible materials.

Gear Details.—Propeller reduction gears may be divided into two classes—spur and planetary. The *spur* type consists of two gears with straight teeth, a small one on the crankshaft, with a larger one on the propeller shaft. Figure 80 illustrates a gear of this type. The propeller shaft is carried on roller bearings, with a ball bearing to take the thrust of the propeller. The second type of propeller reduction gear is called a *planetary* gear, because it contains several small gears or “pinions” which revolve about

their axes and also travel in a circle, in a manner similar to the planets around the sun. Planetary gears may be of either the

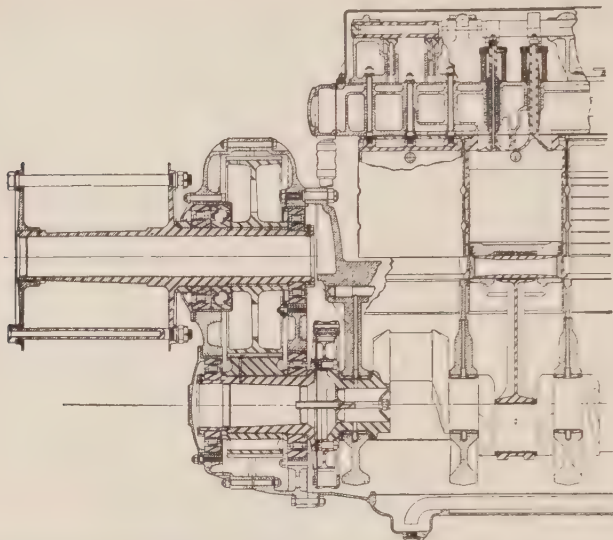


FIG. 80.—Spur-type propeller-reduction gear. (Courtesy Packard Motor Car Co.)

spur or *bevel* type. Figure 81 shows a planetary gear of the bevel type. The crankshaft drives a large bevel gear which drives the

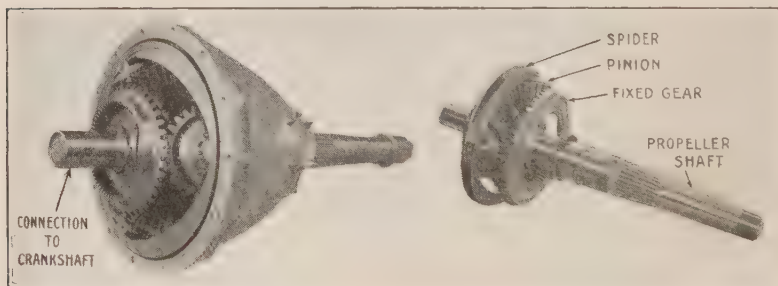


FIG. 81.—Farman bevel planetary reduction gear: (a) gear in place in gear housing; (b) gear removed from housing, showing planets, spider, and stationary gear. (Courtesy Automotive Industries, and Société des Avions H. & M. Farman.)

bevel *planets*. These mesh with another large bevel gear which is held stationary. The propeller shaft is driven by the *spider* or

framework on which the planet gears are mounted. This causes the propeller shaft to run at considerably less than the speed of the crankshaft, the exact ratio depending upon the relative number of teeth in the two large gears. Such a gear is particularly adapted to radial engines where the propeller shaft must be on the same center line as the crankshaft.

TYPES OF ENGINES

Airplane engines are usually classified in accordance with the arrangement of their cylinders. The number of cylinders depends somewhat upon the type but principally upon the size of the engine. For very small engines, as few as two or three cylinders may be used, but in the case of medium and large sizes, it becomes very important to avoid severe vibration, and this is accomplished by using a relatively large number of cylinders and arranging them, as far as possible, to balance each other. Most airplane engines have cylinders of less than $6\frac{1}{2}$ -in. bore and 8-in. stroke, while the largest-size cylinder which is being used successfully at the present time in an airplane engine is of $8\frac{5}{8}$ -in. bore and 12-in. stroke.

The various airplane engine types are as follows:

Vertical Engine.—An engine having its cylinders arranged vertically above or below the crankshaft, in a single row.

V Engine.—An engine having its cylinders arranged in two rows, in the form of the letter V, both rows of cylinders being connected to the same crankshaft.

W Engine.—An engine having its cylinders arranged in three rows, all connected to the same crankshaft, the three rows of cylinders, when viewed from the front, forming a figure similar to the letter W.

X Engine.—An engine having four rows of cylinders, in the form of the letter X when viewed from the front and all connected to the same crankshaft.

Flat Engine.—An engine having cylinders arranged in two horizontal rows on opposite sides of the crankshaft. The two-cylinder "opposed" engine is a special case of the flat engine, used on some small airplanes.

Inverted Engine.—An engine of the vertical, V or W type having its cylinders hung below the crankshaft.

Radial Engine.—An engine having stationary cylinders arranged radially, *i.e.*, like the spokes of a wheel, around a common crankshaft. The usual type is a single-row radial, but radial engines may be made in more than one row, *i.e.*, one “wheel” of cylinders behind another.

Rotary Engine.—An engine, usually of the radial type, in which the cylinders and crankcase revolve about a stationary crankshaft.

Barrel Engine.—An engine having its cylinders arranged around the crankshaft with their axes parallel to the shaft. This is sometimes called the “revolver type,” since the cylinders are arranged like the chambers of a revolver. This type is not in practical use at the present time.

EFFECT OF CYLINDER ARRANGEMENT ON VIBRATION

The number and arrangement of the cylinders affect very much the vibration characteristics of the engine. Engine vibration comes from two sources, one of which is the succeeding impulses from the various cylinders. The fewer the cylinders, and the larger they are, the greater will be this form of vibration. Engines with fewer than five cylinders are suitable only in small sizes, where the magnitude of each cylinder impulse is small.

Another form of vibration is due to the movement of the connecting rods and pistons. With certain cylinder arrangements, the movement of the rods and pistons in some cylinders is equal and opposite to that in other cylinders, and the vibrations offset each other. Such an engine is said to be in mechanical balance and may be used without counterweights or other devices to reduce mechanical vibration. The six- and eight-cylinder vertical engines are well balanced in this respect. V, X, and W engines having rows of six or eight cylinders each are also in good mechanical balance. Rotary engines, having no reciprocating parts, are in excellent mechanical balance. Radial engines having three or more cylinders are balanced by *counterweights* on the crankshaft. The common engine types which do not have good mechanical balance are the four-cylinder vertical and the eight-cylinder V engines. These engines can be used in the smaller sizes only, for in large sizes the lack of mechanical balance constitutes a very serious objection.

CHOICE OF TYPE

Of the various types mentioned, the rotary engine is now practically obsolete, due to the large amount of power that is wasted in wind resistance against the rotating cylinders. The radial engine lends itself particularly well to air cooling. Furthermore, it is relatively simple and particularly easy to overhaul and repair, even when the engine is in place in the airplane. The flat engine appears interesting because of the possibility of its being carried inside the wing of a large airplane. It is probable that multicylinder flat engines will be developed as large airplanes become more numerous. The inverted engine, which may be of the vertical, V, or W type, has the distinct advantage over other types in offering the minimum of interference to the vision forward of the pilot in a tractor airplane. It has the further advantage that the exhaust is discharged below the fuselage and so does not require long pipes or manifolds to keep the exhaust gases from annoying the pilot or passengers.

It cannot be said that any one of the types listed is best for all airplanes. The type selected for a given airplane depends on a great many considerations. It may, however, be said that for engines up to 150 hp. the vertical or single-row radial type is usually best, while the more complicated types, such as the V, X, W, and double-row radial are generally used for engines of over 550 hp. In the range from 150 to 550 hp., the V and single-row radial types are most common.

TYPICAL ENGINES

Tables III and IV give data concerning some of the modern airplane engines now in general use. A few of the more typical ones will now be described in detail.

A. D. C. CIRRUS ENGINE

The Cirrus engine (Fig. 82) is a vertical, air-cooled, four-cylinder engine, of British design, rated at 75 hp. at 1,800 r.p.m. The propeller slip stream furnishes the air necessary for cooling. Air enters a rectangular sheet-metal compartment on the exhaust

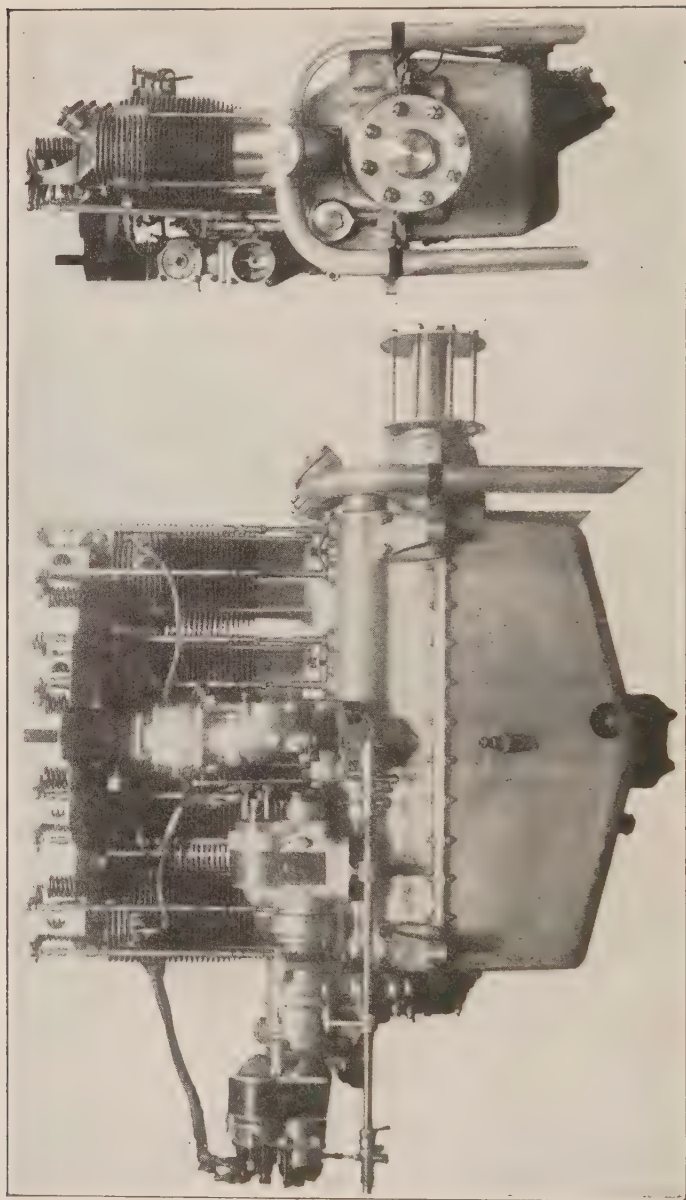


FIG. 82.—A. D. C. Cirrus engine, right side and front views. (Courtesy Aircraft Disposal Co., Ltd.)

side of the engine. From here the air passes through the openings between the cylinders and valve ports into the atmosphere. The general arrangement of such a cooling system is shown diagrammatically in Fig. 83.

Cylinders.—Each cylinder has a bore of 4.33 in. and a stroke of 5.12 in., the total piston displacement being 302 cu. in. The cylinder barrel is made of cast iron with integral cooling fins. The cylinder head is of cast aluminum alloy, also with cooling fins, and is held against the top of the cylinder barrel by four long bolts which pass down the outside of the cylinder barrel to the crankcase. There is a copper gasket between the cylinder head and barrel. The valve seats are made of aluminum bronze.

Valves.—Each cylinder has two valves located vertically in the cylinder head. These are opened, through rocker arms and push rods, by means of a camshaft situated inside the crankcase. The valves are closed by helical springs, a pair of concentric springs surrounding each valve stem.

Pistons.—The pistons are of aluminum alloy and are fitted with three cast-iron rings each. The piston pin is of hardened steel.

Connecting Rods.—The connecting rods are made of forged aluminum alloy. The upper end bears directly on the piston pin, while the lower end is fitted with a babbitt bearing in a bronze shell. The bearing shell is clamped between the two sections of the lower end of the connecting rod by two steel bolts.

Crankshaft.—The crankshaft has four cranks and is carried in five bearings—one at each end, and one between each pair of cranks. The front and rear bearings are of the roller type, while the other bearings consist of bronze shells with babbitt linings. Mounted on the shaft at the extreme front end of the crankcase

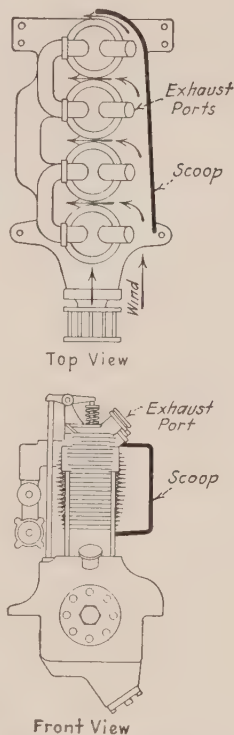


FIG. 83.—Method of cooling vertical engine.

is the *thrust* bearing. This is a ball bearing whose function is to transmit the thrust, or pull, of the propeller on the crankshaft to the crankcase. The crankcase, in turn, is fastened to the airplane and pulls it along through the air.

Crankcase.—The crankcase is made of two aluminum-alloy castings. The upper, or main, part of the crankcase carries the crankshaft bearings and supports the cylinders. On either side of the main crankcase are two projections, or “feet,” by means of which the engine is bolted to the airplane structure. The lower part of the crankcase forms an oil tank which carries the oil supply for this engine. For large engines, the oil tank is usually separate, but in small vertical or V engines, enough oil may be carried in the crankcase, as in this instance.

Lubrication.—At the bottom of the lower crankcase is an oil pump driven by the crankshaft. This pump takes oil from the reservoir in the lower crankcase and forces it through external pipes to the main crankshaft bearings. On leaving the pump, the oil is passed through a fine-mesh screen which is designed to prevent foreign matter from getting into the bearings. From the ends of the main crankshaft bearings, the oil is thrown out by centrifugal action into aluminum “scoops” on the crank arms which deliver it to the hollow crankpins. From the inside of the crankpins, the centrifugal force carries the oil through holes to the lower connecting-rod bearings. Oil thrown off the lower connecting-rod bearings reaches the piston pins, cylinders, and pistons and keeps them well lubricated. The camshaft, being inside the crankcase, continually receives oil thrown off the crankpins. Pipes from the oil pump are led to the gears at the rear end of the engine and, also, to the thrust bearing at the forward end. After lubricating the various parts of the engine, the oil falls back into the crankcase, where it is recirculated by the pump.

Auxiliaries.—This engine is provided with two magnetos, mounted on one side toward the rear and driven through gears from the crankshaft. Each of these magnetos supplies four cylinders, there being two spark plugs in each cylinder. A single carbureter and inlet manifold are located on one side of the engine. The weight of this engine is 285 lb., or about 3.8 lb. per rated horsepower.

THE WRIGHT WHIRLWIND ENGINE

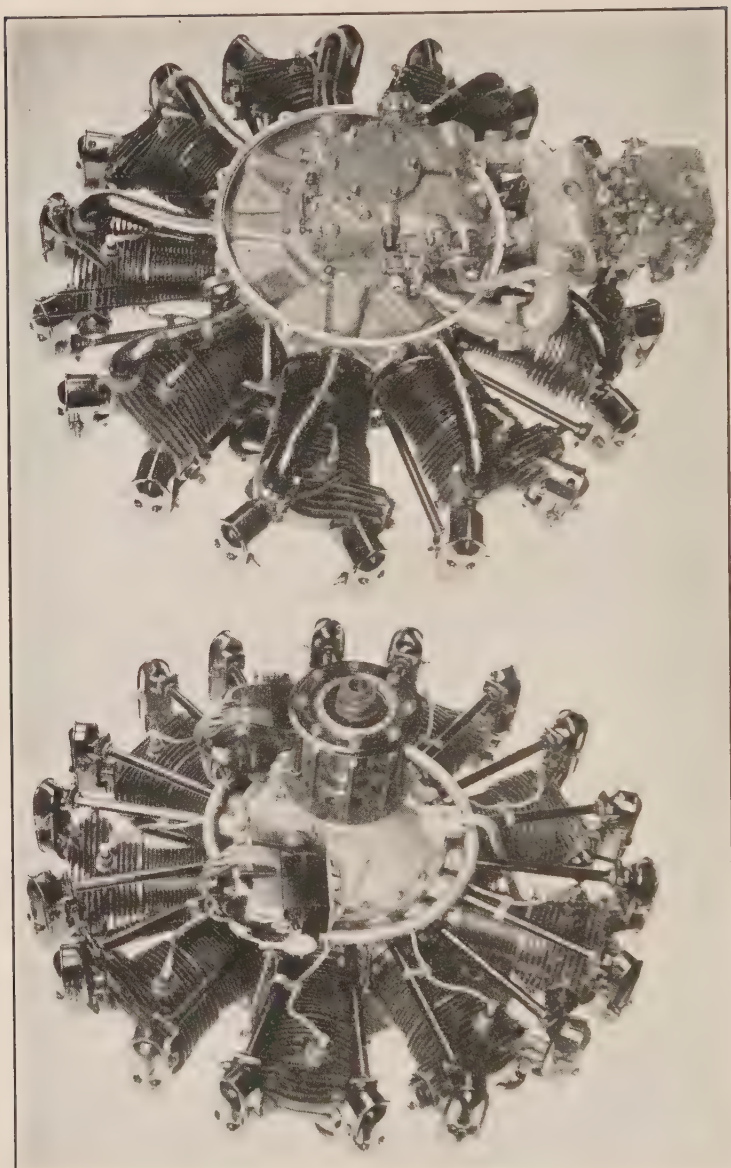
This engine, made famous by Lindbergh's flight across the Atlantic, is a nine-cylinder, air-cooled radial, rated at 220 hp. at 1,800 r.p.m. Figure 84 is a photograph of this engine, and Fig. 85 is a cross-section drawing, showing its internal parts.

Cylinders.—Each cylinder has a bore of $4\frac{1}{2}$ in. and a stroke of $5\frac{1}{2}$ inches. The total piston displacement is 788 cu. in. The cylinder barrels are made of steel forgings, open at both ends. Near the lower end of each barrel is a flange for bolting to the crankcase, while the upper end is threaded to receive the cast-aluminum cylinder head, which is screwed upon it. The cylinder head contains the valves and valve ports and the bronze valve seats. Both cylinder barrel and head are equipped with fins for air cooling. Those on the barrel are machined, while those on the head are formed in the process of casting.

Valves.—There is one intake and one exhaust valve in each cylinder, operated through push rods and rocker arms from a disk-shaped cam located in the forward part of the crankcase. The cam is driven by gears from the crankshaft and carries four lobes. The entire valve gear, including valve springs, rocker arms, and push rods, is enclosed to protect it from water and dirt.

Pistons.—The pistons are cast of a special aluminum alloy. They each carry five cast-iron rings and a hardened-steel piston pin. The pin "floats;" that is, it may turn in both the piston and the connecting rod. To prevent the piston pin from sliding sideward and "scoring" the cylinder, it is provided with rounded aluminum plugs at each end.

Connecting Rods.—A photograph of the connecting rods and pistons as they are assembled in the engine is shown in Fig. 86. Number 1 cylinder, which is at the top, is equipped with what is called the *master* connecting rod. This connecting rod has a babbitt-lined bearing on the crankpin at its lower end. The portion surrounding this bearing is equipped with holes to receive the *hinge* pins. Each of the other cylinders has an *articulated* connecting rod, which is connected by means of the hinge pin to the master connecting rod. Each of the connecting rods, master or articulated, is connected to the piston at its outer end by means of the piston pin.



Front

Rear

Fig. 84.—Wright Whirlwind engine, front and rear views. (Courtesy Wright Aeronautical Corp.)

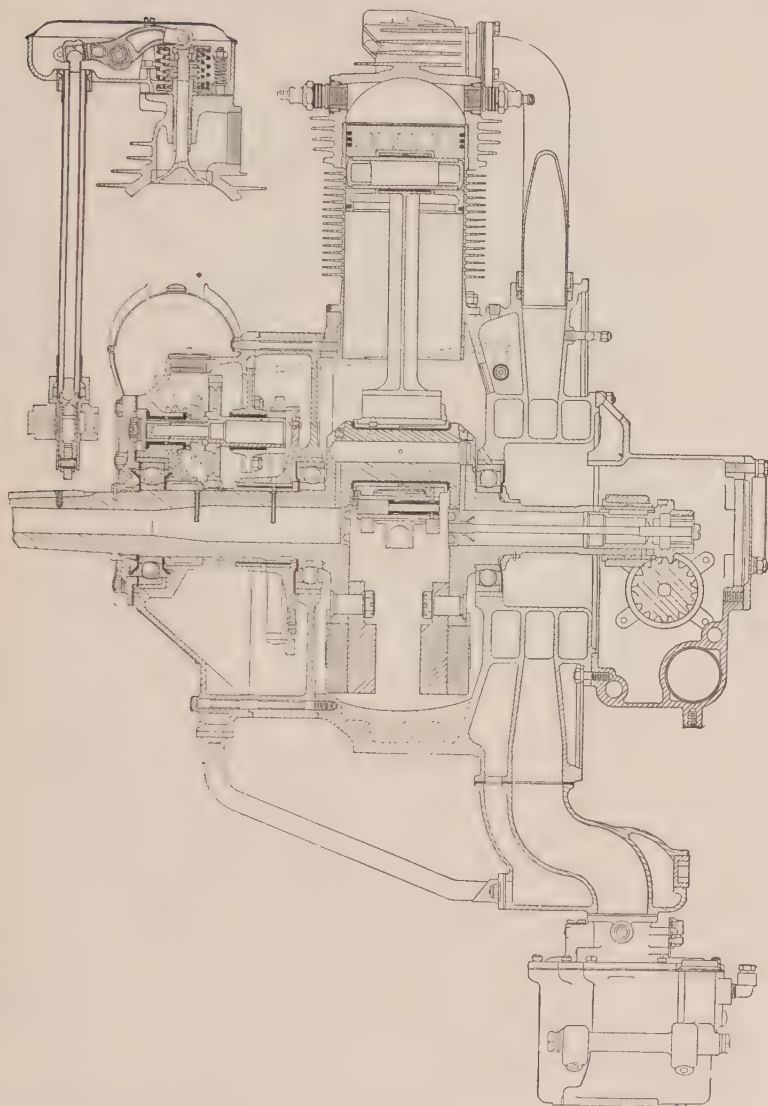


FIG. 85.—Wright Whirlwind engine, cross-section. (Courtesy Wright Aeronautical Corp.)

Crankcase.—The crankcase is made of aluminum-alloy castings in four sections—the front section, which contains the thrust bearing and cam gears; the intermediate section, which carries the rest of the valve gear and the front crank bearing; the main section, containing the crank and connecting rods; and the rear section which carries the various auxiliaries.

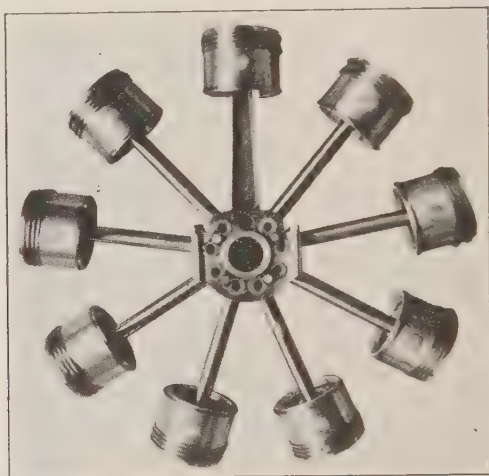


FIG. 86.—Connecting rods of Wright Whirlwind engine. (Courtesy Wright Aeronautical Corp.)

Crankshaft.—The crankshaft is made from an alloy-steel forging and has a single crankpin, counterbalanced with bronze and steel counterweights. The propeller hub is mounted on its forward end. Behind this is the ball thrust bearing and the cam drive gear. The cam is supported on the crankshaft by a babbitt-lined bearing, just in front of the forward main bearing. The two main bearings are of the ball type. A gear to drive the various auxiliaries is mounted on the rear end of the crankshaft, together with a toothed clutch to be engaged by the starter. The crankshaft is hollow and provided with oil passages from end to end.

Carbureter.—The carbureter (Fig. 77), located underneath the rear of the crankcase, delivers the mixture of air and fuel into three ring-shaped passages cast in the crankcase, just behind the cylinders. From these passages, pipes are led to each of the nine intake ports.

Lubrication.—An oil pump, driven from the gear on the rear of the crankshaft, takes oil from an external tank and delivers it through a strainer to the central passage in the crankshaft. From here it is distributed through holes to the various gears and bearings. The pistons, piston pins, and cylinder walls are lubricated by the oil thrown off from the crankpin bearing. Oil which drains to the bottom of the various sections of the crankcase is drawn off by two scavenging pumps and returned to the external oil tank. .

Ignition.—Each cylinder has two spark plugs, and there are two magnetos, one for each set of plugs. The magnetos are mounted on the front crankcase section just behind the propeller and are driven through gears from the crankshaft.

Mounting.—The rear section of the crankcase carries a circular flange with eight bolt holes, by means of which the engine is attached to the "mounting ring" in the airplane. This engine weighs, complete, about 510 lb.

AIR-COOLED LIBERTY

Figures 87 and 88 show an air-cooled, inverted, V-type engine of 12 cylinders, rated at 400 hp. at 1,800 r.p.m. This is called the air-cooled Liberty, since a large number of parts from the water-cooled Liberty have been used in its construction. The pistons, cylinders, and valve gear are of new design, and, unlike the water-cooled Liberty, this engine is of the inverted type.

Cooling.—Air at high velocity, due to the motion of the airplane through the air and to the propeller slip stream, enters the V opening between the two front cylinders. The top and back of the V are covered by a sheet-metal cowling. The exhaust ports and exhaust valves are inside the V, so as to receive the blast of cooling air directly. From inside the V, the air flows out between the cylinders into compartments on each side, formed by cowlings not shown in the figure. From the side compartments, the air passes into the atmosphere through openings on either side near the back of the engine.

Cylinders.—The cylinder construction is the same as that used on the Wright Whirlwind—namely, a steel barrel with integral steel fins, screwed into a cast-aluminum-alloy cylinder head fitted with bronze valve seats.

Valves and Valve Gear.—The valves are operated by two long “overhead” camshafts, one for each row of cylinders. These are mounted in cast-aluminum housings bolted to the cylinder heads. The camshafts carry an exhaust and intake cam for each cylinder, which operate the valves through rocker arms. There is a removable cover, on the housing, under each rocker arm.

Pistons.—The pistons are made of cast aluminum alloy and are quite similar to those of the two engines already described.

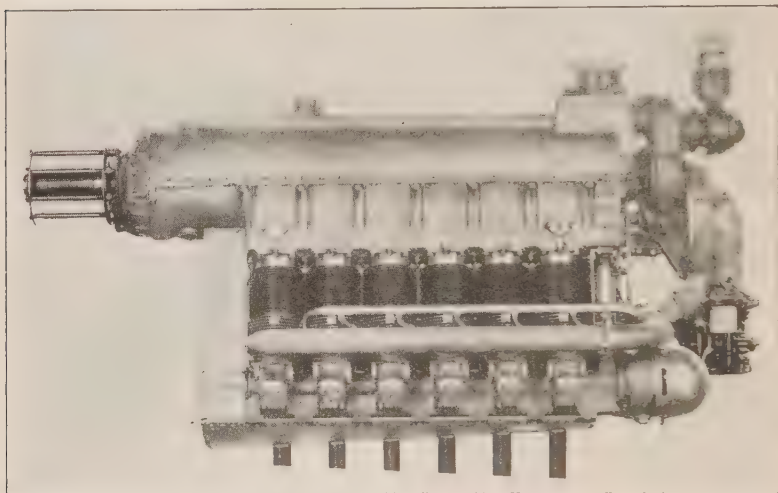


FIG. 87.—Air-cooled inverted Liberty engine, geared model. (Courtesy Allison Engineering Co.)

Connecting Rods. —In the V-type engine, two connecting rods must connect to each crankpin, and in this particular engine, this is accomplished by what is known as a *forked* connecting-rod construction. This type of rod is illustrated in Fig. 89. One of the rods is forked at its big end and carries a bronze, or steel, bearing shell lined on the inside with babbitt. The other, or “plain” connecting rod, is narrow at its big end, fits inside the fork, and bears on the outside of the cylindrical bearing shell of the forked rod. If the bearing shell is of steel, the big end of the plain connecting rod must be lined with babbitt metal. Both the rods are divided and bolted together at their lower end, so that they can be assembled around the bearing shell and crank-

pin. The bearing shell is also divided, so that it can be assembled in place around the crankpin.

Crankshaft.—The crankshaft, made from a single steel forging, has six cranks and runs on seven bronze, babbitt-lined bearings. A ball thrust bearing is located near the front end.

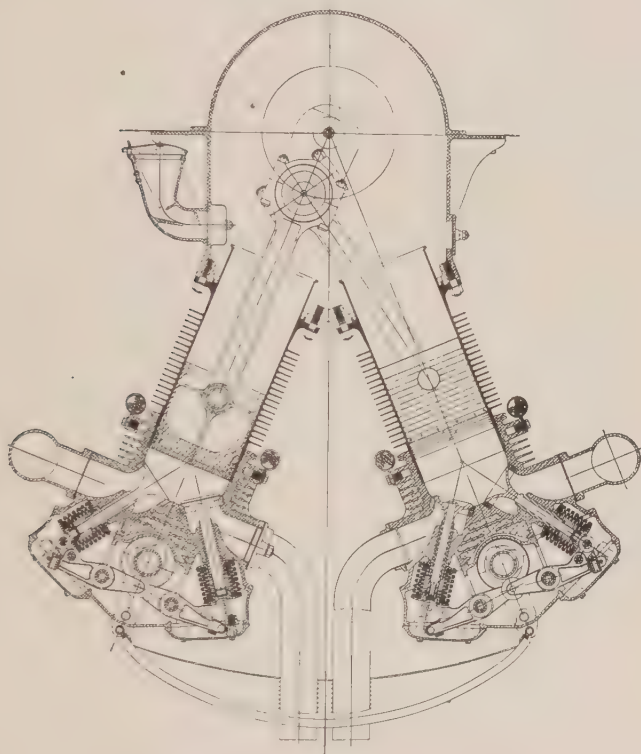


FIG. 88.—Air-cooled inverted Liberty engine, cross-section. (Courtesy Allison Engineering Co.)

Crankcase.—The crankcase is made of two aluminum-alloy castings, bolted together along the center line of the crankshaft. The lower part carries the cylinders and the lower halves of the crankshaft bearings. The cylinders project into the lower crankcase for a distance of about 2 in., so that oil which collects on the crankcase does not flow down into them. The upper part of

the crankcase carries the upper halves of the bearings and the main oil-distributing passages and the pumps.

Lubrication.—There are three gear oil pumps, located in an aluminum housing bolted to the top of the crankcase at the rear. These are driven through bevel gears and a vertical shaft from the crankshaft. The *pressure* pump draws oil from an external tank and delivers it through a screen to a long pipe



FIG. 89.—Forked- and plain-type connecting rods. (Courtesy U. S. Army Air Corps.)

carried in the upper crankcase. From here the oil flows to the crankshaft bearings, into the hollow crankshaft, and through holes in the crankpins to the crankpin bearings. The piston pins, pistons, and cylinders are lubricated by oil sprayed from the crankpins. A pipe is led from the main oil-supply pipe to the bore of each hollow camshaft at the front end. Holes in the camshaft serve to lubricate the camshaft bearings and rocker arms. Excess oil from the camshaft housings is pumped back to the crankcase by means of a small oil pump driven from the rear end of each camshaft. The two scavenging pumps take oil which accumulates in the crankcase and return it to the external oil tank, from where it is recirculated by the pressure pump.

Intake System.—A single carburetor is located at the rear of the engine. This supplies air and fuel to the inlet side of a high-speed centrifugal blower driven through gears from the rear end of the crankshaft. This blower acts as a low-altitude supercharger and assists in mixing thoroughly the fuel vapor with the air. From the blower casing, the mixture is led to the intake ports by means of a single long manifold on the outside of each bank of cylinders.

Propeller Reduction Gear.—This engine is often supplied with a planetary propeller reduction gear of 0.6 ratio, shown in the illustration (Fig. 87).

Auxiliaries.—In addition to the oil pumps and blower, the two camshafts and a small electric generator are driven through bevel gears and shafts from the rear end of the crankshaft. An electric starter is mounted behind the blower. A battery-system ignition distributor is mounted on the rear of each camshaft housing and driven at half engine speed by the camshaft. Each distributor supplies one of the two spark plugs in each cylinder.

SIDDELEY JAGUAR

Figure 90 illustrates a 14-cylinder, double-row, air-cooled radial, the Siddeley Jaguar, a British design, rated at 385 hp. at 1,700 r.p.m. In order to secure moderate-size cylinders and

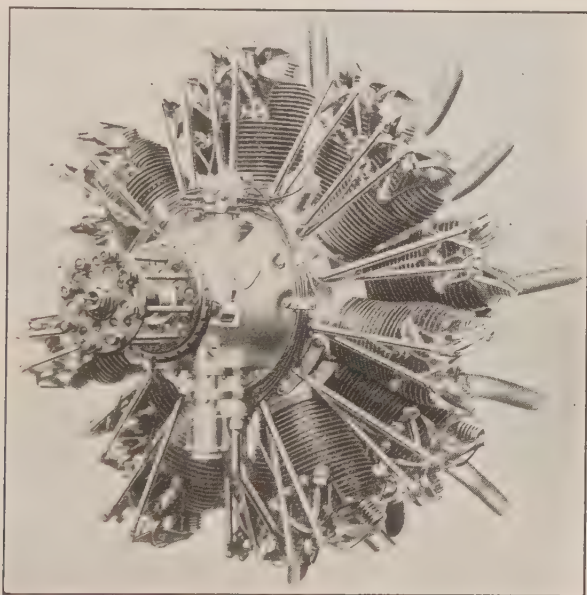


FIG. 90.—Armstrong-Siddeley Jaguar engine. (Courtesy Armstrong-Siddeley, Ltd.)

a small over-all diameter, the designers, in this case, resorted to two rows of seven radial cylinders each. The construction of this engine is very similar to that of the Wright Whirlwind engine previously described, the main difference, aside from the double row of cylinders, being that the crankshaft has two cranks

instead of one. It is evident that the double-row radial is a rather complex design as compared to the single-row radial, and, therefore, it has not been used by many manufacturers.

CURTISS CHIEFTAIN

An engine which bears some resemblance to both the V and the radial types is illustrated in Fig. 91. This is the Curtiss Chieftain rated at 600 hp. at 2,400 r.p.m. It is essentially a double-row radial with six cylinders in each row, but it differs

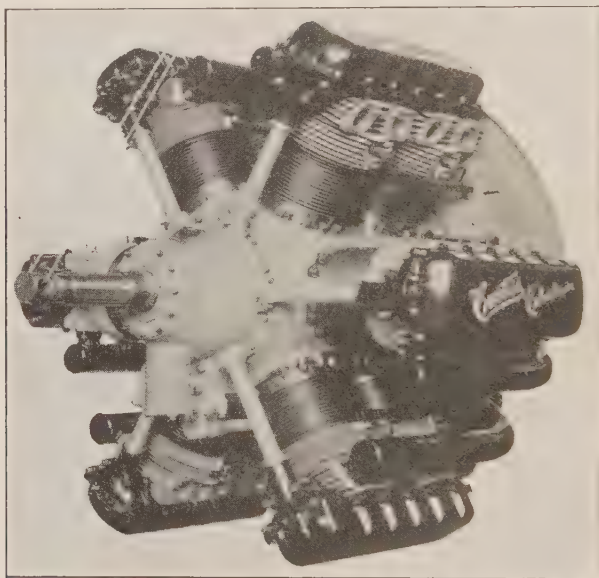


FIG. 91.—Curtiss Chieftain engine. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

from the Jaguar in that the cylinders of the rear row are directly behind those of the front row and the valves are operated by means of overhead camshafts, two of which are located in an oiltight housing bolted to each pair of cylinders. The cylinders are of similar construction to those previously described but have two intake and two exhaust valves each. For cooling, the cylinders are cowed in groups of four, and each group is cowed and cooled in the same manner as in the case of a V engine. Air

enters the front of the V of each group and is forced to pass between and around the cylinders, since the top and back of each V are covered by cowling. Each group of four cylinders exhausts toward the inside of its V. This engine represents a compromise between the radial and the V engine, since it retains much of the short length and ease of mounting of the radial without the large diameter which a radial of such high power would necessarily have.

• OTHER AIR-COOLED TYPES

It is perfectly possible to build the air-cooled engine in other arrangements, such as the X type, or the W, but there are no air-cooled engines of these types in general use at the present time. Several X-type air-cooled engines are in the process of development, however, and it is probable that this type will eventually be available in the large sizes.

WATER-COOLED ENGINES

Water-cooled engines are built in all of the different types and cylinder arrangements previously mentioned. For small sizes, the vertical engine has been widely used, especially in Europe, but at the present time most water-cooled airplane engines are built as V, W, or X types.

CURTISS CONQUEROR

Figure 92 shows a typical modern water-cooled engine of the V type, the Curtiss 12-cylinder Conqueror, rated at 600 hp. at 2,400 r.p.m. This engine is similar in general arrangement to the air-cooled Liberty, except that its cylinders are fitted with water jackets instead of cooling fins and it is not inverted. The cylinders are made in two rows, or *banks*, of six each. The water jackets and cylinder heads of each bank are in the form of a single aluminum casting, into which the steel cylinder barrels are screwed. The valve seats are of bronze, as in the case of many air-cooled engines. This engine has four valves in each cylinder, two intake and two exhaust. Two separate overhead camshafts are used on each bank of cylinders, each pair being driven through an inclined shaft and gearing at the rear end of the

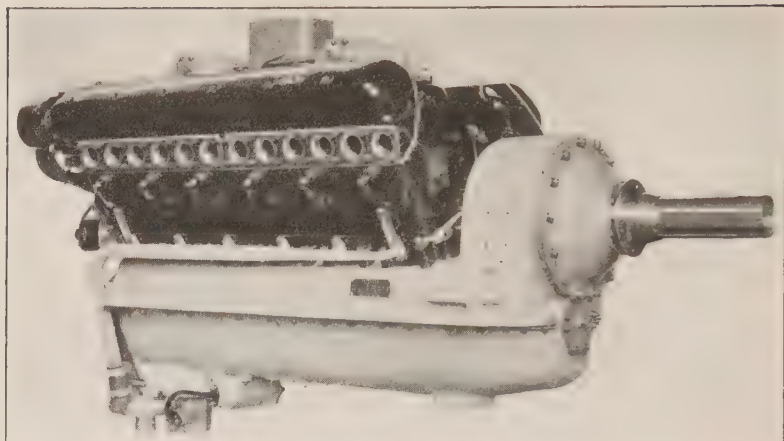


FIG. 92.—Curtiss Conqueror engine, geared model. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)

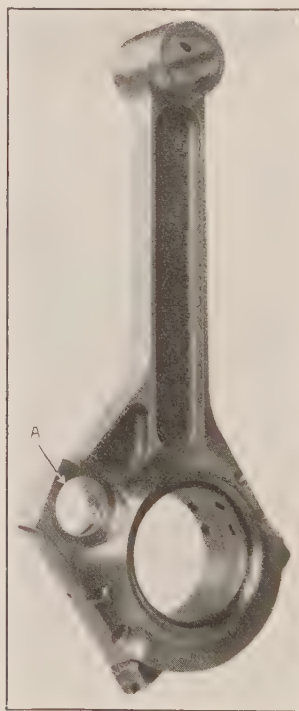


FIG. 93.—Master connecting rod for V engine. Hinge pin for articulated rod is clamped in hole A. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)

engine. All of the valve gear is completely housed. The connecting rod construction differs from that of the air-cooled Liberty. In this case, one of the two connecting rods which bear on each crankpin is of the *master* type and carries a hinge pin to which the *articulated* connecting rod is fastened. This construction is shown in Fig. 93. The carbureters and intake manifolds are carried inside the V, with the double magneto at the rear and the oil and water pumps on the bottom of the crankcase at the rear end. This engine is built both with and without a propeller reduction gear.

OTHER WATER-COOLED TYPES

Figure 94 shows a typical 12-cylinder W-type engine, the Napier Lion of British manufacture; and Fig. 95, the Packard X

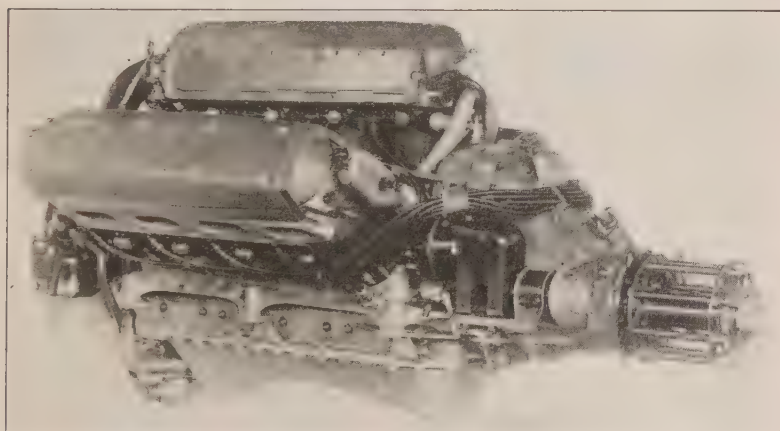


FIG. 94.—Napier Lion racing engine. (Courtesy D. Napier & Son., Ltd.)

engine. Both of these engines have steel cylinders with integral steel cylinder heads and welded sheet-steel water jackets. In each case, the valve ports and camshafts are carried in a single cast-aluminum housing fastened to the cylinder heads of each bank of cylinders. The master and articulated system of connecting rods is used in both cases. The main crankshaft bearings of the Napier are of the roller type, while those of the Packard are plain bearings of very large diameter formed by the circular

crank checks. In other details, these engines are quite similar to those already described. The statistics regarding size, weight, power, etc., of these engines are given in Table IV, together with data for a number of other representative water-cooled airplane engines.

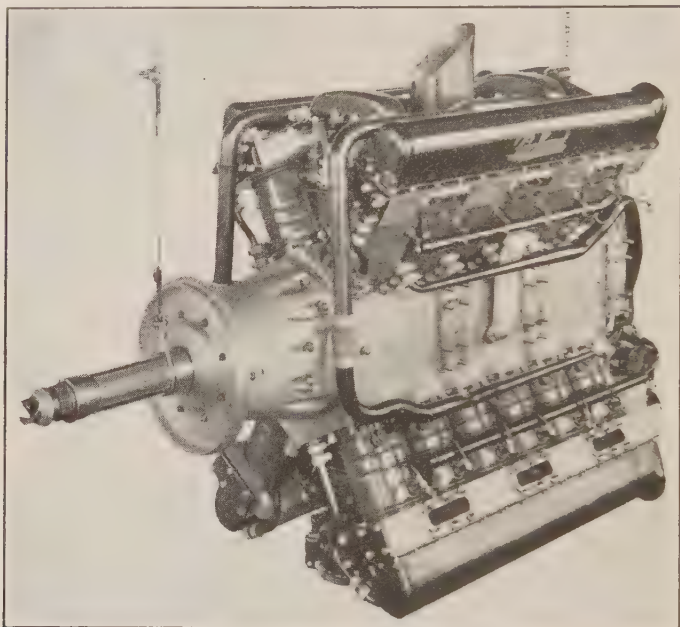


FIG. 95.—Packard X engine. (Courtesy Packard Motor Car Co.)

FUTURE ENGINES

While the internal-combustion gasoline engine fulfils the requirements of the airplane better than any other type, it possesses certain distinct disadvantages. One of these is that it uses a fuel which is relatively expensive and extremely inflammable. Much work has been and is being done toward making the internal-combustion engine capable of using less inflammable and cheaper fuels. Principal among these is the "fuel oil" which remains after gasoline and kerosene have been extracted from petroleum. There are, at present, engines which will operate on fuel oil with high efficiency, but they have not yet

been developed to a point where they are so suitable for airplane use as the gasoline engine. It is quite possible, however, that in the not very distant future the fuel-oil engine will reach the point where it may be used for airplanes.

Another probable future development is that of engines using the two-stroke cycle. These may be of either the gasoline or the fuel-oil type. The great advantage of the two-stroke cycle, or *two-cycle*, engine is that the admission of the fresh charge and the exhausting of the burned gases may be done by a high-speed rotary pump, leaving the engine cylinders free to perform a compression and power stroke on every revolution of the crankshaft. Thus, a lighter engine for the same power output may be expected when this type of engine is developed to the point where each power stroke gives somewhere nearly as much power as the power stroke of a corresponding four-cycle engine and when such difficulties as high fuel consumption and lack of flexibility are satisfactorily overcome.

The *steam engine* has been suggested for aircraft propulsion, since it may burn fuel oil, but the fact that it requires a very large and heavy condenser, also a boiler, burners, and very complicated control apparatus, makes it appear improbable that this type of engine will ever be generally used for airplanes.

Another form of engine which has been suggested is the *internal-combustion turbine*. This type of engine, however, has never been developed to a point where it is more than an interesting experiment. There are very serious difficulties in the way of developing the internal-combustion turbine to a point where it might be at all practicable for airplane propulsion.

TABLE III.—PRINCIPAL CHARACTERISTICS OF SOME TYPICAL AIR-COOLED AIRPLANE ENGINES, 1928

Manufacturer	Model	Rated		Num- ber of cylin- ders	Bore, inches	Stroke, inches	Com- pres- sion ratio	Propel- ler gear ratio	Num- ber of valves per cylind- er	Weight, pounds	
		Horse- power	Revolutions per minute							Total	Per horse- power
Fairchild-Caminez (A).....	447-C	135	1,000	4	5 $\frac{1}{8}$	4 $\frac{1}{2}$	5.2	Direct*	2	360	2.67
Warner Aircraft Company (A)	Starab	110	1,850	7	4 $\frac{1}{4}$	4 $\frac{1}{4}$	...	Direct	2	270	2.45
Wright Aero. Corp. (A)	Whirlwind C	220	1,800	9	4 $\frac{1}{2}$	5 $\frac{1}{2}$	5.4	Direct	2	510	2.31
Wright Aero. Corp. (A)...	Cyclone	525	1,900	9	6	6 $\frac{7}{8}$	5.3	0.5†	2	760	1.45
Pratt & Whitney (A).....	Wasp B	450	2,100	9	5 $\frac{3}{4}$	5 $\frac{3}{4}$	5.0	Direct	2	660	1.47
Pratt & Whitney (A).....	Hornet	525	1,900	9	6 $\frac{1}{8}$	6 $\frac{3}{8}$	5 $\frac{1}{4}$	0.5†	2	750	1.43
Curtiss A. and M. Co. (A)...	Cheftain	600	2,200	12	5 $\frac{5}{8}$	5 $\frac{1}{2}$	...	Direct	4	900	1.50
Allison Engineering Co. (A)	Liberty A C	410	1,800	12	4 $\frac{5}{8}$	7	5.3	0.6†	2	1,000	2.44
A. D. C. Aircraft Ltd. (B)...	Cirrus II	75	1,800	4	4.33	5.12	4.9	Direct	2	285	3.80
De Havilland (B).....	Gipsy	85	1,900	4	4 $\frac{1}{2}$	5 $\frac{1}{16}$	5.0	Direct	2	280	3.30
Bristol, Ltd. (B).....	Cherub III	33	2,900	2	3.54	3.8	5.5	Direct	2	95	2.88
Bristol, Ltd. (B).....	Jupiter VI, A. M.	440	1,700	9	5.75	7.5	5.3	0.5†	4	720	1.63
Bristol, Ltd. (B).....	Mercury (racer)	800	2,500	9	5.75	6.5	...	Direct	4	680	0.85
Armstrong-Siddeley (B).....	Genet	65	1,850	5	4	4	5.2	Direct	2	200	3.08
Armstrong-Siddeley (B).....	Jaguar III	385	1,700	14	5	5 $\frac{1}{2}$	5.0	0.657†	2	800	2.08
Lorraine-Dietrich (F).....	100 CV	100	1,350	5	4.92	5.51	5.0	Direct	2	331	3.31
Lorraine-Dietrich (F).....	230 CV	230	1,800	7	5.31	5.90	5.0	Direct	2	575	2.50
Anzani (F).....	6-80	80	1,500	6	4.13	4.92	5.1	Direct	2	225	2.81
Siemens & Halske (G)...	Sh 11	96	1,750	7	3.91	4.72	...	Direct	2	333	3.47

(A)—American (B)—British (F)—French (G)—German

* Each cylinder fires every revolution, therefore equivalent to a reduction gear of 0.5 ratio.

† Made in both direct-drive and geared models—weight given is for direct drive.

TABLE IV.—PRINCIPAL CHARACTERISTICS OF TYPICAL WATER-COOLED AIRPLANE ENGINES, 1928

Manufacturer	Model	Rated		Type	Num- ber cylin- ders	Bore, inches	Stroke, inches	Com- pres- sion ratio	Propel- ler gear ratio	Num- ber valves per cylin- der	Weight, pounds	
		Horse- power	Revolu- tions per minute								Total	Per horse- power (rated)
Curtiss A. & M. Co. (A)	OX-5*	90	1,400	V 90°	8	4	5	4.9	Direct	2	377	4.2
U. S. Government	Liberty 12-A*	420	1,700	V 45°	12	5	7	5.4	Direct	2	875	2.08
Curtiss A. & M. Co. (A)	F-12†	435	2,300	V 60°	12	4.5	6	5.3	Direct	4	680	1.56
Curtiss A. & M. Co. (A)	Conqueror	600	2,400	V 60°	12	5.1 ₈	6.1 ₄	5.8	0.61	4	755	1.26
Packard Motor Car Co. (A)	3A-1500	600	2,500	V 60°†	12	5.3 ₈	5.1 ₂	5.5	0.507†	4	760	1.27
Packard Motor Car Co. (A)	3A-2500	770	2,000	V 60°	12	6.3 ₈	6.1 ₂	5.4	0.506†	4	1,160	1.51
Packard Motor Car Co. (A)	X Racer	1,250	2,700	X	24	5.3 ₈	5	...	Direct	4	1,402	1.12
D. Napier & Son., Ltd. (B)	Lion 11B	470	2,000	W-60°	12	5.1 ₂	5.1 ₈	5.8	0.658	4	966	2.06
D. Napier & Son., Ltd. (B)	Racer	875	3,300	W-60°	12	5.1 ₂	5.1 ₈	10.0	0.765	4	930	1.06
Rolls-Royce Ltd. (B)	F-12	490	2,250	V-60°	12	5.1 ₂	5.1 ₈	6.0	0.552	4	865	1.77
Rolls-Royce Ltd. (B)	Condor III	670	1,900	V 60°	12	5.1 ₂	7.2 ₂	5.3	0.477	4	1,320	1.97
W. Beardmore & Co., Ltd. (B)	Cyclone	950	1,350	Vertical	6	8.5 ₈	12	5.4	Direct	4	2,150	2.27
Farman (F)	18-W I	550	2,800	W-40°-I	18	4.33	4.92	6.0	0.393	4	820	1.49
Hispano-Suiza (F)	12-M	500	2,000	V-60°	12	5.12	6.69	6.0	Direct†	4	882	1.76
Hispano-Suiza (F)	12-N	650	2,000	V-60°	12	5.9	6.69	6.0	Direct†	2	1,000	1.54
Lorraine-Dierich (F)	450 CV.	450	1,850	W-60°	12	4.72	7.08	5.5	0.647†	2	850	1.89
Lorraine-Dierich (F)	650 CV.	650	2,000	W-40°	18	4.72	7.08	6.0	0.647†	2	1,190	1.83
Junkers (G)	L-5	280	1,500	Vertical	6	6.3	7.48	5.5	Direct	2	1,705	2.32
B. M. W. (G)	V I	600	1,500	V-60°	12	6.29	7.48	5.5	0.626†	2	1,120	1.87
F. I. A. T. (I)	A-83 (racer)	970	2,500	V-60°	12	5.71	6.88	6.0	Direct	4	920	0.95

(I)—Italian

(G)—German

(F)—French

(B)—British

(A)—American

* Obsolete—in use but no longer manufactured.

† Made in both direct and geared models. Weight given is for direct drive.

‡ Made in both upright and inverted models.

CHAPTER VIII

THE PROPELLER

To drive an airplane through the air, it is necessary to apply to it continuously a force sufficient to overcome the air resistance of all its parts. It is the function of the propeller to furnish this force, which is called the *propeller thrust*, and so to impart energy to the airplane. To be able to exert a thrust, the propeller must be kept turning and so must continually be supplied with mechanical energy from the engine. The power output of the propeller to the airplane may be expressed by multiplying its thrust by the distance through which it moves forward in unit time as the airplane advances. When the propeller thrust is measured in pounds and the speed of the airplane, in feet per second, the power output of the propeller is measured in foot-pounds per second, and this value divided by 550 gives the output of the propeller in horsepower. The input into the propeller, which is also expressed in horsepower, is evidently the same as the power output of the engine. Naturally, it is desirable that the power output of the propeller be high in proportion to the input, that is, that the *propeller efficiency* be high, for propeller efficiency is the ratio obtained by dividing the power output of the propeller by the power input. For example, if in an airplane traveling at the rate of 176 ft. per second (120 miles per hour) the propeller thrust is 516 lb., then the power output or *thrust horsepower* of the propeller is $\frac{176 \times 516}{550} = 165$ hp. If the engine horsepower is 220, then the propeller efficiency is $\frac{165}{220} = 0.75$, that is, 75 per cent.

Description and Nomenclature.—Figure 96 shows a conventional wood airplane propeller. Such a propeller generally has two arms, called *blades*, which unite at the center to form the *boss*. The edge of the blade on the side toward which the propeller is turning is called the *leading edge*, and the other is the

trailing edge, and the extreme outer end of the blade is the *tip*. These terms are used with the same meanings as for airfoils. The shape of cross-section of the blade, except near the boss, is essentially that of an airfoil. The propeller *diameter* is that of the circle described by the tips of the blades as the propeller turns. The side of the blade which strikes the air first, and which is usually comparatively flat, corresponds to the undersurface of an airfoil and is called the *load face*, or simply the *face*. The other side of the blade, which corresponds to the upper surface of an airfoil, is called the *back*.

A wood propeller is usually mounted on a steel *hub*, as shown in the figure. The central portion of the hub passes through

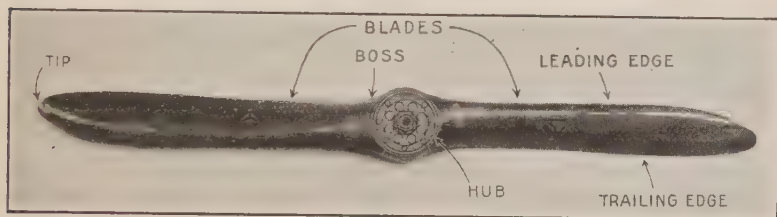


FIG. 96.—Wood propeller. The back of the blades is shown, and the front of the hub. (Courtesy Materiel Division, U. S. Army Air Corps.)

a hole in the propeller boss and at the rear has an integral flange against which the boss rests. A detachable flange, splined or keyed to the front of the hub, is held against the front face of the boss by bolts which pass through both flanges and the propeller. The inside of the hub is machined to fit over the end of the engine crankshaft and is held in place by nuts in front. Splines or keys are employed to compel the hub to turn with the shaft.

Action of the Propeller.—The propeller gives a thrust in essentially the same way that an airfoil gives lift; for the propeller in turning drives the air backward at a speed greater than it would have if it had not encountered the propeller. The increase in rearward velocity imparted to the air by the propeller is analogous to the downward component of velocity imparted by an airfoil, and in each case the reaction is the same. A force is developed which tends to push the wing or propeller blade in a direction opposite to that in which the air is being driven.

Just as the airfoil can exert a lift only by deflecting downward the air which strikes it, so the propeller can develop a thrust only by imparting an increased backward speed to the air which it encounters. Fundamentally, the propeller is simply a device for driving a jet of air backward, though the word "jet" must here be interpreted in a rather broad sense, for the jet or *slip stream* may be 15 ft. in diameter and may be moving backward at a velocity only 15 per cent greater than the speed of the relative wind. There is no known way for propelling an airplane other than by driving a jet of air backward.

It can be demonstrated mathematically, and confirmed by tests, that the greatest efficiency that can be reached by a propeller or by any other means of jet propulsion depends upon the relation of the speed of air in the jet to that of the undisturbed air. The slower the relative speed of the jet the higher can be the efficiency. The efficiency, therefore, can be much better with a large, relatively slow slip stream than with a small, high-speed jet, and it is apparent that any scheme for propelling an ordinary airplane by a high-speed jet from some sort of gas generator inevitably leads to an efficiency much lower than that of an ordinary propeller.

The Propeller as an Airfoil.—According to the most widely adopted theory of propeller action, a propeller blade such as is shown in Fig. 96 is to be regarded as composed of a series of

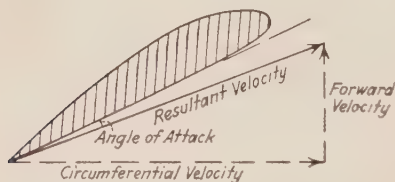


FIG. 97.—The propeller airfoil.

short airfoils, not alike in shape or angle but changing smoothly and continuously from the boss out to the tip. Each short length of blade or airfoil, as shown in Fig. 97, has two components of motion relative to the air. The first of these is one along the

circumference of a circle; it can easily be found when the speed of rotation is known. The other, at right angles to the first, is due to the forward motion of the airplane and so is equal to the airplane speed. From these two components, the velocity and direction of the relative wind on each section of airfoil can be calculated.

A drawing of the propeller blade gives the shape of each little airfoil and, also, the angle between its chord and the propeller axis, so that the angle between the airfoil chord and the relative wind can be determined. This angle is obviously the angle of attack of the airfoil, as shown in Fig. 97. From wind-tunnel test data for models of the different little airfoils, it is possible to calculate the total lift and drag of the whole propeller blade and so to determine the thrust that it will give and the power required to drive it.

Such a direct calculation from wind-tunnel results is not accurate, however, because of several influences that come in to modify the assumed conditions. The air begins to gain speed in front of the propeller, so that the forward speed of the blade relative to the air which actually strikes it is greater than that of the airplane relative to the undisturbed air. This speeding up of the air in front of the propeller is known as *inflow*. The propeller blade tends, also, to drag the air along with it as it turns, so that the air behind the propeller is given a whirling motion in addition to its backward impulse. This whirling motion is known as *race rotation* and, like the slipstream velocity, begins to appear ahead of the propeller. The true air speed of the airfoil element in the circumferential path is, therefore, decreased by the velocity of the race rotation. Both of these influences affect the true angle of attack of every part of the blade and so modify its lift and drag. Another uncertainty arises from the fact that, since each short airfoil merges imperceptibly into the next, it is impossible to fix any definite value for its span. The aspect ratio for the little airfoil is, therefore, unknown, and its effect on the lift coefficient cannot well be estimated. Finally, each blade of the propeller interferes with the other just as do the wings of a biplane. The combined effect of all these factors is enough to account for the unsatisfactory results of attempts to design propellers exclusively from airfoil test data.

In spite of these difficulties, the theory is good enough to establish two general principles that govern the choice of the airfoils which determine the shape of the blade. Since the propeller should give a large thrust in proportion to the required turning effort, the airfoil shapes selected should have good L/D

ratios. It is not advantageous, however, to use shapes which have very high lift coefficients, for then the drag as well as the lift for a given length of blade would be large, and the propeller diameter would have to be small in order not to require excessive engine power. A small diameter reduces the size of the slip stream, increases its speed, and so diminishes the propeller efficiency.

It is interesting to note that the diameter of the slip stream a short distance behind the propeller is considerably less than that of the propeller itself. As very little air passes through the propeller near the center, the slip stream really has the form of a hollow cylinder, of which the inside diameter is about three-tenths that of the propeller and the outside diameter about eight-tenths.

Model-propeller Tests.—Since tests of model airfoils are inadequate for propeller design, it has been found desirable to make the tests upon a small model propeller instead. As a test in still air would not give correct results, the model propeller is mounted in a moving stream of air or on the end of a long arm which is whirled around a central pivot. There is a definite relation between the characteristics of the model propeller and those of the full-size one of like shape, just as there is between the characteristics of the model airfoil and those of the corresponding large wing. This relation can be expressed by equations using coefficients somewhat like airfoil coefficients, so that from the model-propeller test the designer knows what to expect of the full-size propeller.

Adaptation to Working Conditions.—A good propeller is one that is designed for the particular conditions under which it operates. It must, therefore, be adapted to the engine which drives it and to the airplane which it propels. To secure high efficiency, the propeller diameter is usually made as large as permitted by the power of the engine, but there must be a proper clearance between the tips of the propeller and the ground as well as between the propeller and other parts of the airplane. Since the airfoil shapes used for the blades should not be those with very high lift coefficients, the blade sections must not be too thick. A reasonable thickness is necessary for strength, however, and the final shape and diameter usually represent the best compromise possible under the circumstances.

Since the engine is intended to give its rated power at a definite speed, the propeller must be designed to absorb this power at that speed. The speed at which the propeller turns with a given engine depends on the forward speed of the airplane; if the propeller is designed for a forward speed less than that actually developed by the airplane, it will turn too fast, with an adverse effect on the life and reliability of the engine. If, on the other hand, the airplane speed was overestimated, the propeller will not allow the engine to run at the speed necessary for it to give its rated power.

Any propeller has its best efficiency when the ratio between the forward speed and the speed of rotation has a particular value, and while it is not within the power of the designer to increase this efficiency beyond a fairly definite limit, he can make the maximum efficiency occur at almost any desired ratio of speeds. Usually, the propeller is planned to have its best efficiency at the maximum speed of the airplane and the rated speed of the engine, as this combination evidently gives the highest maximum airplane speed. If, however, a high rate of climb is preferred to a high maximum speed in level flight, the propeller is designed to give its best efficiency when the engine speed is somewhat lower than the rated speed and the airplane speed is considerably less than the maximum. Such a propeller is known as a *climbing propeller*.

There have been cases in which a manufacturer, desirous of claiming a high performance for his airplane, has made the high-speed test with one propeller and the climbing test with a different one. This procedure is obviously not a fair representation of the performance of the airplane, unless the prospective purchaser has been specifically informed that the tests were conducted in this way.

The high rotative speeds of modern airplane engines involve a definite loss in propeller efficiency because of the resulting limitation upon propeller diameter. This loss is particularly serious in low-speed airplanes. Under these circumstances, therefore, it is often advantageous to fit the engine with a reduction gear, so that the propeller may turn at a speed much less than that of the engine crankshaft and so be of greater diameter. This should not be done, however, until a study of the whole problem has

shown that the gain in efficiency from the lower propeller speed is more than enough to offset the disadvantages arising from the greater weight of the propeller and from the increased weight and complication of the reduction gear.

Multiple-blade Propellers.—The conventional airplane propeller has two blades, a form which combines low cost and high efficiency. A propeller could be built with only one blade, but a counterweight would be required for balance, and the increased weight and resistance thus involved would undoubtedly offset any advantage that might result from the elimination of the interference between blades. In many cases, however, and particularly in the flying boat and in the amphibian, the largest diameter of two-blade propeller permitted by limitations of clearance is not large enough to absorb the power of the engine unless a very wide and, therefore, inefficient blade is used. To avoid this difficulty both three-blade and four-blade propellers have been adopted, even though the construction of the propeller is thus made more difficult, especially if wood is the material used. With three blades, the effect of blade interference is not much worse than with two, but with four the effect becomes more serious, so that the efficiency of a four-blade propeller may be 4 per cent less than that of the corresponding two-blade propeller. Propellers with more than four blades are not used. Aside from the interference effects, the multiblade propeller always has a smaller diameter and, consequently, a lower efficiency than one with two blades, so that it is ordinarily adopted only where the conditions of installation do not permit using the two-blade type.

Variable-angle Propellers.—The power needed to drive a propeller at any speed depends on the density of the air in which it turns. At high altitudes, therefore, where the air density is low, a given propeller will absorb less power than at sea level. This is a favorable circumstance with the ordinary aircraft engine, which suffers a loss in power with increasing altitude, though the power required to turn the propeller at a given speed does not decrease with altitude quite so rapidly as the engine power decreases, so that there is some loss of engine speed at higher altitudes. When the engine is supercharged, however, the case is quite different, for the supercharged engine may maintain its sea-level power up to a considerable altitude. With such an

engine, a propeller designed to hold the engine down to its rated speed at sea level is too small at altitude and so will allow the engine to overspeed. The propeller must, therefore, be large enough to hold the engine down to its rated speed at the highest altitude at which it is still delivering its sea-level power, that is, at the critical altitude. The propeller is then much too large for sea-level conditions and so prevents the engine from turning at its rated speed. This involves a loss of power and may so reduce the propeller thrust, particularly at low forward speeds, that the airplane may have the greatest difficulty in getting off the ground.

The solution of this difficulty lies in the use of the *variable-angle* propeller, which incorporates a device by which the pilot in flight can change the angle of the propeller blades to the plane of rotation. Such a propeller may be large enough only to hold down the engine to its rated speed at sea level. As the airplane climbs, a change in angle increases the angle of attack of the blades, so that both thrust and power required are increased and the engine is held down to its rated speed. It should be understood that the ordinary non-variable propeller is just as good at some one altitude as the corresponding variable-angle propeller but that it is not so good at other altitudes. The maximum efficiencies of the two propellers may be equal, but the average efficiency of the variable-angle propeller at all altitudes will be much the better. The mechanism for changing the blade angle may be so constructed as to permit this angle to be made negative, so that the direction of thrust is reversed and the propeller pushes back on the airplane instead of pulling it forward. Obviously, this last device is of no use in the air, for a loss of flying speed cannot be permitted, but it is useful in shortening the distance the airplane runs after its wheels have touched the ground. The control for changing the blade angle must be interconnected with the engine controls so that the angle of attack of the blade cannot be made zero with the throttle open. Without this precaution the engine might easily be wrecked by overspeeding if the pilot neglected to close the throttle under conditions when the propeller can absorb much less than the power normally needed to drive it. Evidently, also, the pilot must be careful not to reverse the blade angle until the wheels of

the airplane are on the ground, lest the resulting loss of air speed cause a sudden descent with serious consequences.

Although many variable-angle propellers have been proposed and tested, none has yet reached the stage of extensive use. The difficulty is mainly one of providing sufficient strength and an easily operated mechanism without excessive weight and resistance. With the increasing use of supercharged engines, the need for a practical variable-angle propeller becomes steadily more urgent, and a satisfactory solution of the problem may reasonably be expected.

In concluding this part of the discussion of propellers, it should be mentioned that the conventional airplane propeller is not by any means the inefficient mechanism which many suppose it to be. As there appears to be no way of propelling an aircraft except by driving some sort of jet of air backward, an efficiency of 100 per cent could be attained only with a slip stream of infinitely low velocity and infinitely large diameter—an impossible condition. No device for aircraft propulsion, therefore, can be expected to have an efficiency very near 100 per cent. It is by no means unusual, however, for a modern metal propeller to reach an efficiency of 80 per cent, which may easily be as much as 90 per cent of the maximum possible theoretical efficiency calculated purely from the velocity of the slip stream. It is, therefore, evident that there is not a great deal of room for improvement in efficiency and that no substitute for the conventional propeller is worth much consideration unless it promises to be simpler, lighter, or cheaper.

Propeller Construction.—For many years, most airplane propellers have been made of wood, and, of the many species which have been tried, birch is now considered to be the best. A propeller is not carved from a single piece but is built up of several separate planks, or *laminations*, each of which, in a two-blade propeller, extends from tip to tip. Five to nine separate laminations are used, each about $\frac{3}{4}$ in. thick. After the wood has been carefully inspected for defects and has been dried to remove the excess moisture, the individual laminations are cut roughly to shape and glued together, making an assembly like those shown in Fig. 98. The propeller is then roughly shaped, often by machine, and afterward is carefully finished by

hand. During this process, it is approximately balanced. The tips, and the leading edges of the blades for a considerable distance in, are often covered with a light brass sheathing, which is attached to the blade by means of countersunk wood screws. The heads of the screws are covered with solder, which is filed off to give a smooth surface. This tipping is useful to protect the most exposed parts of the blade from the action of the weather and also from the abrasive effect of dust or pebbles which may be picked up while the propeller is running on the ground. To prevent the penetration of moisture, the propeller is given a coat of aluminum leaf and several of varnish. Finally, it is mounted on a spindle and very carefully balanced.

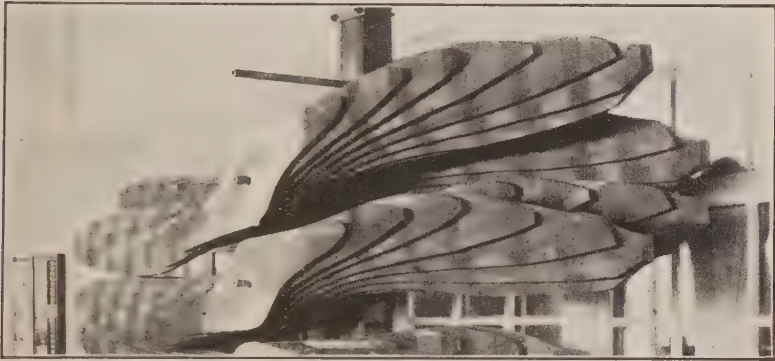
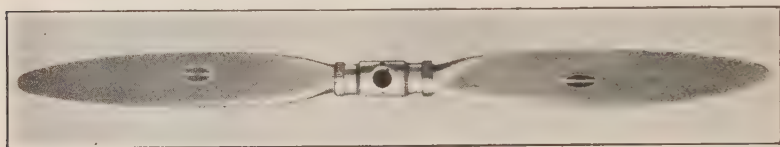


FIG. 98.—Propeller laminations glued before shaping. (Courtesy Materiel Division, U. S. Army Air Corps.)

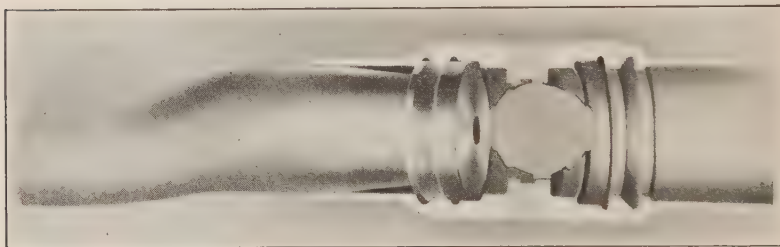
Wood is not entirely satisfactory for propellers, because it is adversely affected both by hot and by damp climates and because its limited strength requires the use of blade forms thicker than those that give best efficiency. On account of these disadvantages, a number of other materials have been tried for propellers. One of these is *micarta*, a fabric impregnated with *bakelite*, a chemical product obtained from carboic acid and widely used for radio panels. The micarta propeller has the great advantage of being entirely unaffected by moisture and temperature, so that its life is great, even in severe service. It is also stronger than the wood propeller. Micarta propellers are formed in one piece under heavy pressure in a mold, the high

cost of which makes the propellers very expensive unless identical propellers are being made in large numbers. The weight of micarta propellers is the same as or slightly less than that of corresponding wooden propellers, and their efficiency may be slightly better.

In recent years, there has been a large increase in the use of metal propellers. Of these, two makes are used in the United States. The first is the Standard Steel propeller, which is shown in Fig. 99. Each blade consists of a single piece of duralumin forged into the proper shape. The butt of the blade fits into a



(a)



(b)

FIG. 99.— The Standard Steel propeller: (a) complete propeller; (b) section showing construction of hub and blade. (Courtesy Standard Steel Propeller Co.)

socket in the hub, and two shoulders prevent it from coming out. The hub is a steel forging made in two parts, held together by heavy clamps which may be easily separated to permit insertion of the blade. The inside of the hub is machined to fit over the end of the engine crankshaft, and large nuts are provided on the front of the shaft to keep the hub in place.

With this construction, it is comparatively easy to replace a damaged blade or to change it for one of more suitable size or shape. In addition, the angle of the blades may be readily changed simply by turning them in their sockets after the clamps have been loosened. This feature is of considerable advantage,

particularly on airplanes of new design, for if it is found, after a test flight, that the engine does not run quite at the proper speed, an appropriate change in blade angle will correct the difficulty. The weight of this propeller is likely to be somewhat more than that of a corresponding wood propeller.

The other make of metal propeller is the Curtiss-Reed, shown in Fig. 100. The whole propeller, including the hub, is forged from a single piece of duralumin. The hub is thus considerably smaller and lighter than that of the Standard Steel propeller but does not permit easy change in blade angle. The weight of the complete propeller is about the same as that of the corresponding wood propeller.

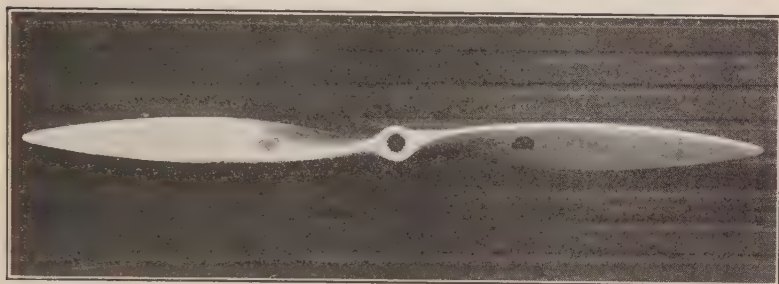


FIG. 100.—Curtiss-Reed propeller. (*Courtesy Curtiss Aeroplane & Motor Co. Inc.*)

Both types of metal propellers, if properly designed, give better efficiencies than the best wood propellers, because the higher strength of the material permits the use of thinner airfoil sections. It is not at all uncommon for the efficiency of a metal propeller to be above 80 per cent, while that of a wood propeller is seldom more than 75 per cent. Since an increase of efficiency means that more engine power is being transformed into the useful work of driving the airplane, it is evident that the increased efficiency of the metal propellers to a large extent justifies their higher cost, particularly as they are unaffected by weather conditions and so have a useful life much longer than that of wood propellers. If a metal propeller happens to strike the ground, the damage is likely to be limited to a bent blade, which can be straightened by proper manipulation and heat treatment. The repaired propeller is substantially as good as before. A damaged wood propeller,

on the other hand, can usually be repaired only by cutting off the damaged portion, an operation that usually leaves it too small for the service for which it was previously used.

No matter what the type of propeller construction, the quality of material and workmanship must be of the very best. The stresses due to centrifugal force and thrust reach very high values, and as the speed of the tips may be as great as 8 miles per minute, it is apparent that if a propeller blade breaks, the energy of the piece which flies off is tremendous. A flying blade is certain to cut through any part of the airplane which it strikes, and if the part destroyed is a vital one, the consequences of a propeller failure may be very serious. A propeller breakage usually wrecks the engine, either by throwing it hopelessly out of balance, or by allowing it to overspeed. It should be mentioned, also, that even when a propeller is turning comparatively slowly on the ground it is capable of inflicting the severest injuries upon anyone who may be so unfortunate as to come within the path of its blades.

CHAPTER IX

THE COMPLETE POWER PLANT

The complete airplane power plant consists of the engine, with carbureters, pumps, and ignition system, the starter, propeller, and propeller hub, cooling system, oil-supply system, fuel-supply system, and engine-control system. The engine and the propeller have already been described in some detail. This chapter will describe the remaining units of the power plant.

COOLING SYSTEM

Air Cooling.—In the case of the air-cooled engine, the cooling system is largely contained within the engine itself. Provision must be made, however, in the design of the engine mounting, cowling, and other parts of the power plant, for supplying air to the cylinders or to the cooling-system intake, and passages must be provided for the cooling air to flow to the atmosphere after it has been used.

Radial-engine Cooling.—In the case of the radial engine, little more is necessary than holes in the cowling to allow the cylinders to project into the propeller slip stream. The cylinders are usually exposed to the direct blast from the propeller, except the lower part of the cylinder barrel, which is covered by the cowling. The holes in the cowling through which the cylinders project must be sufficiently large so that there is a good circulation of air over the lower part of the barrel. Figure 157 (p. 223) illustrates the way in which a radial engine is usually cowed.

Vertical-engine Cooling. The vertical air-cooled engine requires a duct or "scoop" on the exhaust side, as already described in connection with the Cirrus engine. A corresponding duct opening to the rear, on the intake side, is sometimes used. These ducts may be made a part of the engine cowling. For V-type air-cooled engines, the cooling is accomplished as explained

in connection with the air-cooled Liberty. Since the exhaust ports are the hottest portion of an air-cooled cylinder, the air blast is usually directed against the exhaust side. This means that in the case of a V engine, the exhaust ports and exhaust pipes must be on the inside of the V, with the inlet manifold on the outside. X and W types of air-cooled engines are cooled by the same method, since these engines are simply multiples of the V type.

WATER-COOLING SYSTEMS

The cooling system required for water-cooled engines is somewhat more elaborate than that required for air-cooled engines. It consists of the radiator, water-storage tank, piping, and radiator shutters and controls, in addition to the pumps, piping, and jackets which are carried on the engine itself.

Radiators.—The radiator is essentially an arrangement for receiving the hot water from the engine jackets and dividing it up into a large number of small streams which are sent through small tubes or thin sheet-metal passages whose outer surfaces are exposed to a blast of air. In this way, a very large surface in contact with the water on one side is exposed to the cooling action of the air on the other side. Radiators are made in a great variety of shapes and sizes, but they all comprise three essential elements: (1) an intake *header* which collects the water from the piping and distributes it to the various cooling elements of the radiator; (2) the cooling elements or tubes; and (3) an outlet header which collects the water from the cooling elements and delivers it to a pipe through which it runs back to the engine. Radiators may be divided into three classes according to their design, namely, the *core*-type, the *plate*-type, and the *surface*-type radiator. The core-type radiator is one in which the cooling surface takes the form of a compact assembly of small tubes or flat passages. This is the type used on automobiles and on most airplanes in this country. In the plate type, the cooling surface is made up of a large number of flat plates, fastened together in pairs to form a thin, flat water space between each pair of plates. The surface-type radiator is one whose cooling element consists of a thin passage formed by two thin metal sheets, between which the water is forced to circulate, the outer sheet being used

to form part of the outer surface of the wings or other parts of the airplane.

Core Types.—The cooling elements of the core-type radiator have been made in a wide variety of forms, but the one that seems to have proved best for airplane use is made of thin copper tubes whose ends are formed in a hexagonal shape and

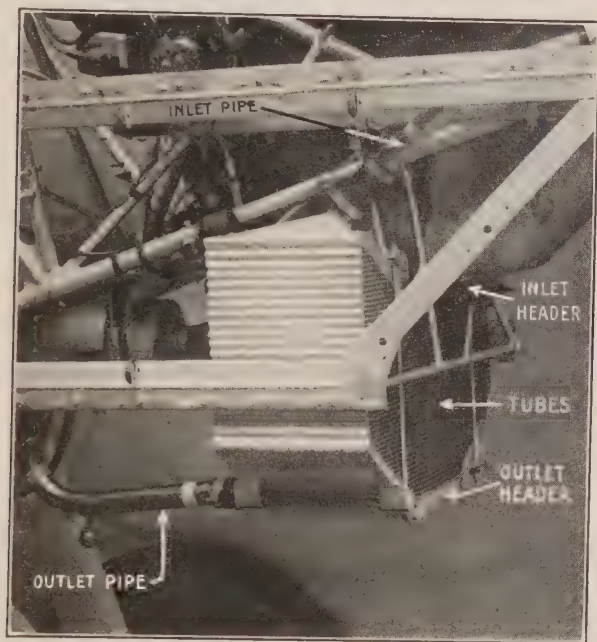


FIG. 101. Cartridge-core radiator. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

soldered together like a honeycomb. This type of core is illustrated in Fig. 101. It is known as the *honeycomb* or *cartridge-core* type of radiator. The length of the tubes varies from 4 to 9 in., depending on the design of the radiator and its location on the airplane.

Plate Radiator.—Figure 102 illustrates a typical plate-type radiator. This is very popular in Europe. The plate radiator is somewhat more "efficient" than the core-type radiator; that is, it will dissipate more heat to the air in proportion to its

parasite resistance. This, of course, is a very valuable characteristic in an airplane, but, on the other hand, the plate radiator is more expensive and much more easily damaged than the core radiator. On account of this, it is not popular in this country.

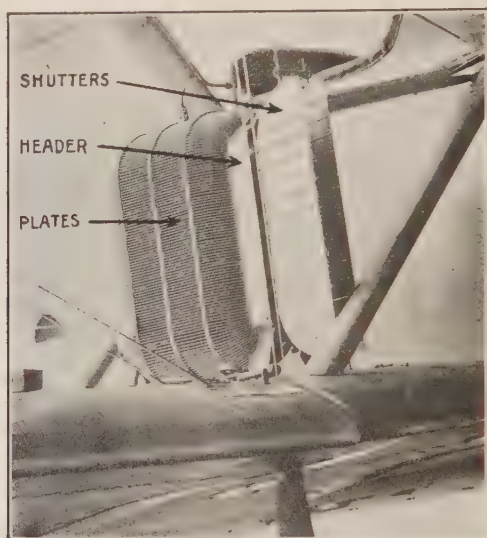


FIG. 102.—Plate-type radiator. (Courtesy *Etablissements Lambelin, and Wright Aeronautical Corp.*)

Surface Radiator.—The surface-type radiator is the most “efficient” of all from the point of view of resistance only. It will be at once apparent that since this type of radiator forms the surface of a wing or fuselage, and since this surface is a necessary part of the airplane, the radiator itself offers no additional resistance to the passage of the airplane through the air, provided that the surface of the radiator is smooth. Some types of surface radiators are corrugated, in which case there is a small increase in drag, but this is very much less than the drag of core or plate radiators. On the other hand, this type of radiator is very heavy, carries a large amount of water, and is exceedingly delicate, being easily damaged by local boiling of the water or by anything which strikes it. It is also extremely expensive to build and interferes somewhat with the airplane design. For these reasons, the surface-type radiator is not used except where

the reduction of parasite resistance is all-important, as in the case of racing airplanes.

RADIATOR DESIGN

Heat Dissipated by Engine.—Heat dissipation may be measured in terms of the British thermal unit, or B.t.u., which is defined as the equivalent of the heat necessary to increase the temperature of 1 lb. of water 1°F. It has been found that water-cooled aircraft engines dissipate about 25 B.t.u. per minute to the cooling water for each horsepower developed at full throttle. For example, an aircraft engine developing 100 hp. will dissipate 2,500 B.t.u. per minute to the cooling water. This means that a radiator must be provided which will give up at least this amount of heat under the most unfavorable cooling conditions that will be encountered in flight when the engine is running at maximum power. The most unfavorable cooling condition is usually maximum climb near sea level in hot weather.

Heat Dissipated by Radiator.—The amount of heat which a radiator will dissipate into the air depends on the following factors: type and design of the radiator, area of radiator surface, velocity of air flowing through the radiator, and difference between the air temperature and the average water temperature in the radiator. Radiators of new type are usually tested in a wind tunnel to determine their characteristics of heat dissipation and parasite resistance under various conditions of air speed, temperature, etc.

Position of Radiator.—Since the cooling power of a radiator depends on the air velocity through it, it is desirable to place the radiator in such a position that the flow of air through it will not be obstructed. If, for some reason, the radiator must be placed in a position where the flow is obstructed, a much larger radiator will be necessary, which will involve increased weight and parasite resistance. An illustration of such a location is the "nose" position, so called because the radiator is placed in the front of the airplane directly ahead of the front engine cylinders. It is evident that in such a position the cylinders and crankcase of the engine will seriously restrict the flow of air through the radiator and a much larger radiator will have to be used than if it were placed outside the fuselage in a

so-called "free-air" position, where the flow of air through the core would be unobstructed. The nose radiator position is sometimes used in low-speed airplanes where head resistance is relatively unimportant and where the very short and direct piping constitutes an advantage. Most modern airplanes using water-cooled engines carry the radiator in a much less obstructed position, however. One widely used position is immediately beneath the engine toward the front of the engine compartment. Such a radiator mounting is shown in Fig. 182 (p. 268). This position of the radiator allows a practically unobstructed flow of air through the core.

Expansion Tank.—In addition to the radiator, the cooling system must include an *expansion* tank. This tank is located at the topmost point in the system and serves to take care of the expansion of the water when it is heated, to carry some reserve water to allow for evaporation, and to provide a place for filling the radiator. When the top of the radiator is the highest point in the system, as in the case of the nose radiator, the tank can be incorporated in the inlet header of the radiator.

Piping.—The piping connecting the engine, expansion tank, and radiator is usually made of sheet steel, brass, or aluminum, with rubber-hose connections to allow some flexibility. The piping must be so arranged that there are no points at which steam may accumulate and so that the whole system may be drained from one point without leaving any water which might give trouble from freezing.

Shutters.—Since the engine is not always operating at full power, and since the air temperature may be far lower than the air temperature for which the radiator was designed, some method of cutting down the heat dissipation from the radiator is necessary. This usually is accomplished by *shutters*, whose function is to reduce the velocity of the air passing through the radiator. These shutters are usually made like the shutters of an ordinary window blind and are controlled from the pilot's seat. Upon throttling down the engine to a low speed, it is necessary for the pilot partially to close the shutters, so that the water will keep warm and the engine temperature will be normal when he is ready to use the full power of the engine again.

Cooling-system Weights.—The weight of a water-cooling system includes not only the weight of the radiator, tank, and piping but also that of the water contained in them and in the engine water jackets. The average airplane water-cooling system using a core- or a plate-type radiator weighs in the neighborhood of $6\frac{1}{10}$ lb. for each rated horsepower of the engine. For example, a 400-hp.-engine water-cooling system would weigh about 240 lb. Practically all this weight, together with all the piping, pumps, and water tanks, is eliminated in the case of the air-cooled engine.

Antifreeze Solutions.—Since water freezes at and below 32°F., it is necessary to add alcohol, glycerin, or some other chemical which will prevent freezing and consequent damage to the cooling system when the airplane is not running.

WATER VERSUS AIR COOLING

The chief advantages of water cooling are uniform temperature of the cylinders and ability to keep the engine warm when idling; radiator surface which can be placed in a favorable position, regardless of the location of the engine; radiators which can be so designed as to offer somewhat less parasite resistance than an air-cooling system of equal capacity. For racing, and similar purposes where maximum speed is all-important, the water-cooled engine with wing surface radiators is preeminent. On the other hand, an air-cooling system weighs much less than a water-cooling system for the same-size engine. For this reason, as well as on account of its simplicity, reliability, and freedom from freezing and boiling, the air-cooling system is rapidly displacing the water-cooling system for most types of aircraft.

FUEL SYSTEMS

The fuel system consists of the fuel-storage tank, fuel piping, and fuel pump, if one is used. It usually includes, also, one or more fine screens or strainers, introduced to prevent foreign matter's going into the carbureter and engine.

Tanks.—Airplane fuel tanks are usually made of aluminum, duralumin, or *ternplate*, which is thin steel plate covered with a protective metallic coating. The aluminum or duralumin tank

is light in weight, but its construction is somewhat difficult because it cannot be soldered with ordinary soft solder. Aluminum and duralumin tanks are usually made by welding together sheets of the material. A disadvantage of the aluminum tank is its liability to corrode in the presence of water. Duralumin is less likely to corrode and has such enormous advantages over ternplate from the point of view of weight that it is one of the common airplane-tank materials at the present time. Ternplate tanks are easily soldered, relatively free from corrosion,

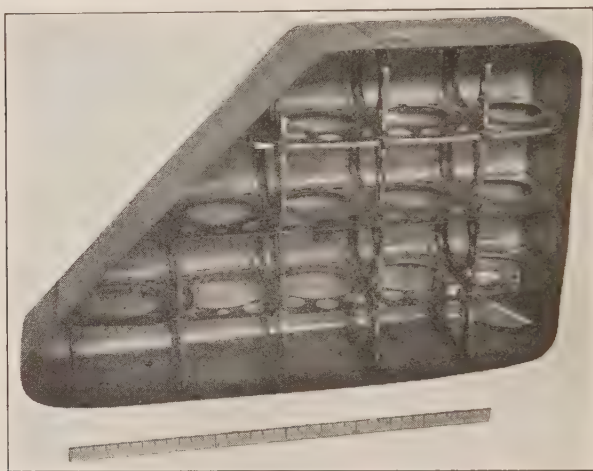
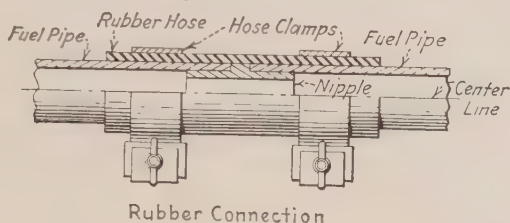


FIG. 103.—Airplane fuel tank, with side removed to show baffle plates. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

and considerably less expensive than aluminum and duralumin tanks. They are very popular for low-priced airplanes. All fuel tanks, except the very smallest, are divided into compartments by *baffle plates*, running across the inside of the tank in two directions. The function of these baffle plates is to keep the fuel from surging in the tank and, also, to brace the sides of the tank and keep them from bulging. Figure 103 shows these baffle plates plainly. Large holes are cut in the baffles at frequent intervals so that the fuel can flow freely between them. Tanks must be provided with a filler cap at the top and with a *sump* or low point in the bottom, from which the fuel can flow. The screen or strainer is often incorporated in the sump.

Fuel Piping.—Copper or duralumin tubing is usually used for fuel. It is very important that the joints between one length of pipe and the next, and between the piping and other parts of the fuel system, be very carefully made to prevent breaking in flight due to vibration or other causes. Two types of joint, illustrated in Fig. 104, are in common use. One is made up of brass fittings fastened to the ends of the tube and screwed together. It is used in places where there is little vibration and where the joint cannot easily be reached for inspection and repair.



Brass Connection

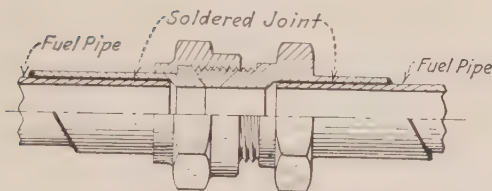


FIG. 104.—Fuel-line connections.

The other type of joint is often used where the fuel line is subject to severe vibration. It consists of a length of special rubber hose, compounded so as to be very resistant to the solvent action of gasoline on rubber. The hose is held on the tubing by clamps, and a little fitting or *nipple* is inserted between the ends of the pipes to keep particles of rubber from getting into the fuel line. The action of the gasoline leaking out between the ends of the tubing and the nipple gradually softens the hose, and it must be replaced at regular intervals. This type of joint will stand a tremendous amount of vibration, however, and seldom fails suddenly.

Fuel Supply.—Whenever possible, the airplane designer locates the fuel tanks far enough above the carbureter so that a fuel pump will not be required. Pumps, like any other mechanical contrivance, are subject to failure, while fuel feed by gravity is very reliable. Unfortunately, it is not always practicable to locate the tanks for gravity feed, and in such cases some form of pump is necessary.

Fuel Pumps.—Airplane gasoline pumps are usually of the gear type, although plunger pumps are sometimes used. Pumps may be driven by the engine or by a small windmill located in the slip stream. The advantage of the latter method is that the pump may be located below the gasoline tank and, therefore, is always primed, while a pump located on the engine often must be primed before it will start. Whatever type of pump is used, there must be some auxiliary system for use in case the pump fails. This may be either a small tank located high up in the airplane, and feeding to the engine by gravity, or a hand-operated pump, which can be used for the emergency. The latter is preferable, for it enables all of the gasoline remaining in the tanks to be used, while the small gravity tank limits the airplane to the flying that can be done before its contents are exhausted. Figure 105 shows a typical fuel system using an engine-driven pump with a hand pump as auxiliary. The various parts are named on the figure. In case the engine pump fails, the hand pump is operated and delivers the fuel through the engine pump to the carbureter. The hand pump is fitted with check valves, so that the engine pump can draw its supply of fuel through it when the hand pump is not operating. In order to prime the engine pump for starting, the hand pump is given a few strokes, which fills the carbureter, after which the engine can be started, and the engine-driven pump maintains the supply of fuel.

Fire Hazard.—The gasoline carried in an airplane constitutes a most serious fire hazard, either during flight or after a "crash." It is difficult to prevent fires after a crash, when the gasoline tanks may be broken and the gasoline spilled over the hot engine parts, but careful design of the fuel system can practically eliminate fires in the air. Fires in the air are usually due to breakage of the fuel pipes. Proper placing of the piping supports, the use in the pipes of materials which will withstand

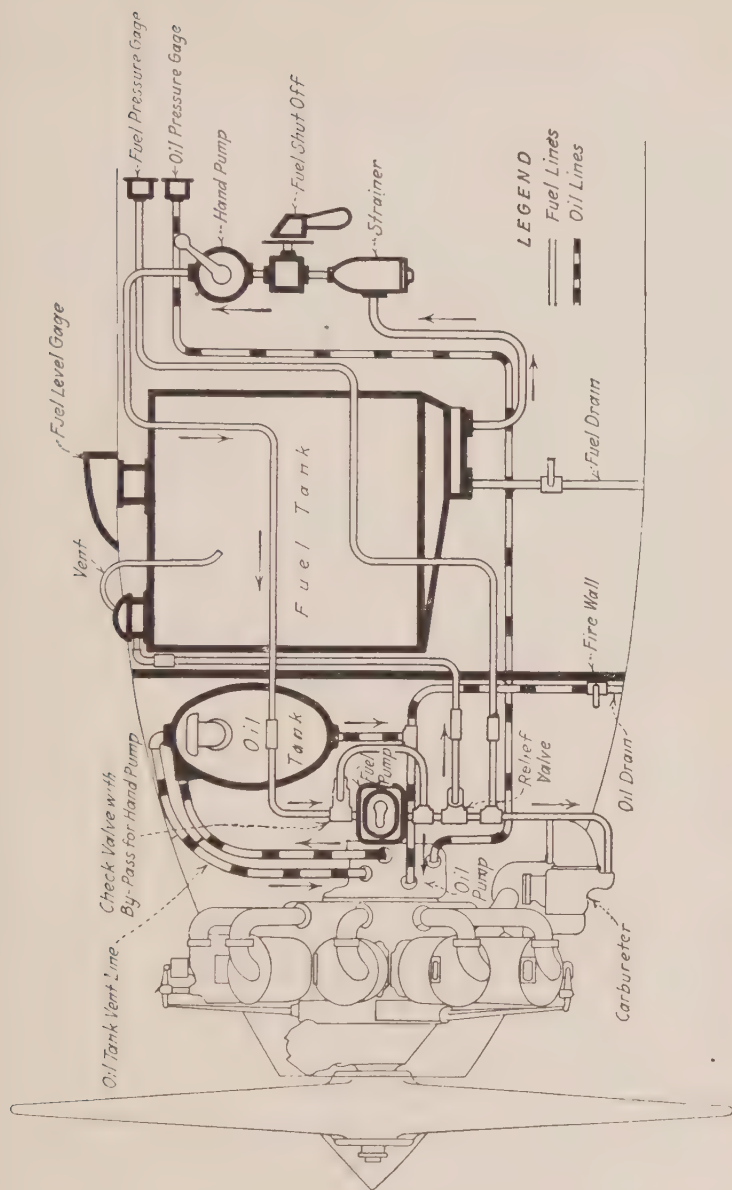


FIG. 105.—Typical fuel and oil systems.

vibration, and the use of proper joints and fittings have achieved remarkable freedom from fires in the air. The main gasoline-supply pipe to the engine is always fitted with an easily accessible shut-off valve for use in case of emergency.

LUBRICATION SYSTEM

In addition to the lubrication pump and passages in the engine, an external oil tank is usually necessary, together with piping and, sometimes, an oil cooler. The tank may be made of brass, ternalplate, duralumin, or aluminum. It is so designed that it can never be entirely filled with oil, as some space must always be left at the top for the oil to expand when it becomes heated. This space must be vented to the atmosphere, usually through the engine crankcase. From the bottom of the tank, a pipe is led to the engine-oil-pump inlet, and from there the oil is distributed to the bearings, as previously explained. The scavenging pumps take the oil from the crankcase and return it to the oil tank. Some engines give up so much heat to their oil that a cooler is necessary. This may be in the form of a small radiator similar to a water radiator, or, if the engine be water cooled, it may consist of a coil of piping or a group of tubes in contact with the cooling water. The latter arrangement has the advantage that the oil is heated by the water in starting and when the engine is running, the oil, being warmer than the water, is cooled. Figure 105 shows a typical oil system.

CONTROL SYSTEM

The controls necessary for the aircraft power plant always include a lever for operating the throttle, a valve for shutting off the fuel supply, and a switch for the ignition circuit. If variable spark timing, carbureter mixture control, supercharger, or radiator shutters are used, controls for these must also be provided. All of these controls are led to hand levers near the pilot's seat, placed in such a position that the pilot can reach them quickly and easily. The throttle, spark, mixture, and supercharger control, being very important, are usually placed near the left hand of the pilot, who uses his right hand for operating the stick. These levers should be connected to the corresponding

levers on the engine by means of rods or tubes which slide back and forth along their axes in order to transmit the control motion. Cables running over pulleys are sometimes used in large airplanes, where the engine is at a great distance from the pilot's seat, but these should be avoided wherever possible. The radiator shutters are controlled by a similar arrangement, but the shutter lever need not be quite so close to the pilot or so convenient for him as the ones previously mentioned. The fuel system must always have a shut-off valve, so that in case anything happens to the engine or it catches fire, the main fuel supply can be quickly and easily shut off. This is usually accomplished by leading the main supply pipe near enough so that a valve can be placed convenient to the pilot. If this is not possible, the valve is placed at some distance, with a long rod connected to a lever convenient for the pilot to reach. If the airplane contains more than one fuel tank, it is usual to provide the pilot with valves by means of which he can turn on and off the various tanks independently. The ignition system must always have a shut-off switch within easy reach of the pilot. It is, of course, extremely important that all controls be very carefully made, because the results might be quite serious if any of them failed to function properly.

STARTERS

As was mentioned in a previous chapter, no internal-combustion engine is self-starting, because it is necessary to produce the suction and compression strokes before the power stroke can occur. In order to start, therefore, such engines must be rotated by outside power, or the cylinders must be supplied, by artificial means, with a combustible mixture. Starting airplane engines by turning the propeller by hand is very dangerous and difficult, and some form of starting device is, therefore, most desirable. For aircraft engines, the starter must be very light and compact and, at the same time, very powerful, since most airplane engines are quite large and require considerable power to turn them, especially when cold. Starters which rotate the crankshaft may be driven by hand, electricity, or compressed air. Several such starters are illustrated in Fig. 106.

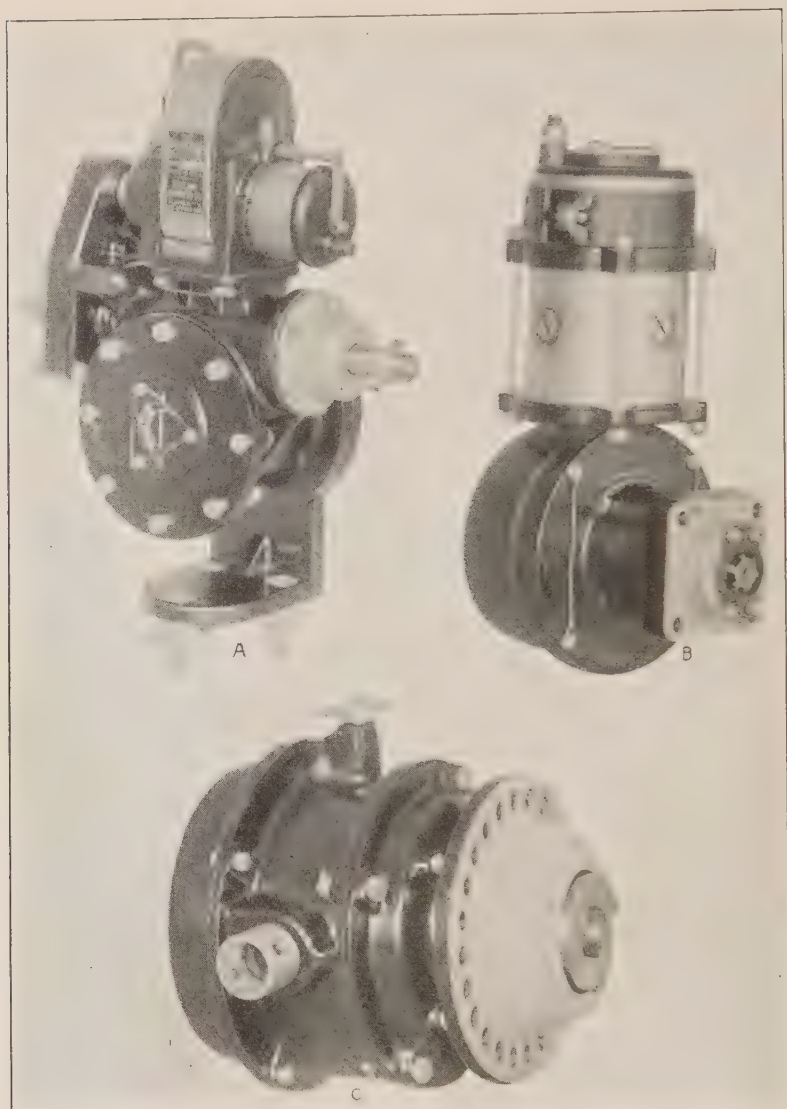


FIG. 106.—Starters: (a) hand-crank type with "booster" magneto; (b) electric type; (c) hand inertia type. (Courtesy Eclipse Machine Co.)

Hand Starters.—Hand starters are usually arranged to connect with the rear end of the crankshaft, and carry a hand crank which is geared down so as to reduce the turning force necessary. They also contain some form of non-reversible clutch to protect the operator in case of a “kick back.” One of the most popular types of hand starter, called the *inertia starter*, is one in which the crank is used to accelerate a small flywheel. When the flywheel is brought up to a very high speed, a lever is moved, which throws in a clutch connecting the flywheel, through gearing, to the engine crankshaft. The energy in the revolving flywheel serves to turn the crankshaft rapidly for several revolutions, which is usually sufficient to secure a start.

Electric Starters.—Electric starters are very similar to hand starters except that a small electric motor is substituted for the handcrank. They may be either of the direct cranking or inertia type. A storage battery must be carried in the airplane, unless the starter is to be used only on the flying field, in which case current may be supplied through long wires, from the hangar. A switch is placed in the pilot’s cockpit, by means of which he can turn on the current and rotate the engine crankshaft.

Air Starters.—Compressed-air starters utilize the energy contained in a tank of air at very high pressure. This may be used to drive a small compressed-air engine which is geared to the crankshaft, or the air may be sent through a distributing valve to the cylinders of the main engine. In the latter type, the compressed air is sent through a small carbureter which mixes with it gasoline vapor. This mixture is delivered to those cylinders which are on the firing stroke. A hand operated magneto is provided to cause a spark to pass in these cylinders, and if the mixture of compressed air and gasoline vapor is correct, the ignition of the charge in a cylinder on the firing stroke will rotate the crankshaft sufficiently so that the other cylinders will fire, and the engine will usually start. The compressed air for an air starter may be furnished by a small engine-driven compressor, by a handpump, or the tank may be “pumped up” to a very high pressure before the flight, by means of a compressor on the ground.

Comparison of Starters.—Hand starters are light and simple compared to the other types. The simple, geared hand crank

usually requires someone outside the airplane to operate it. With the inertia type, the pilot can climb into his seat and start the engine after having brought the flywheel up to speed by means of a crank outside the cockpit. The electric starter is easy to operate from the pilot's seat, but the battery is heavy, requires frequent attention, and constitutes a fire hazard. The number of possible attempts to start is limited by the capacity of the battery, but this is usually ample even for a very "balky" engine. The air starter is usually lighter than the electric starter, but the number of attempts to start is quite limited with an air tank of moderate size and the operator often uses up his air before a balky engine is started. Air starters should be provided with a handpump for use in such an emergency.

SUPERCHARGERS

The general principles of supercharging have been discussed in Chap. VII. The application of the supercharger to airplanes is as yet in the early stages of development, but two distinct types

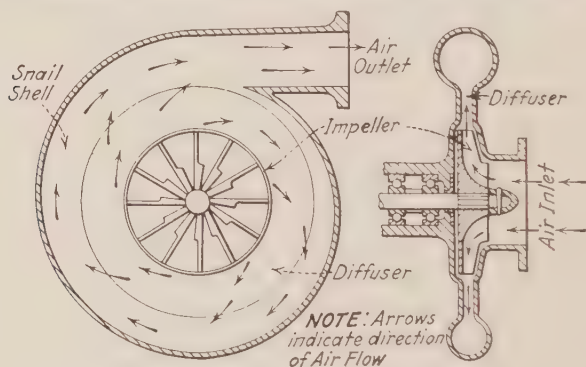


FIG. 107.—Sections of centrifugal supercharger.

have already been applied to military airplanes with great success.

The *centrifugal supercharger*, shown in Fig. 107, consists of a bladed wheel within a casing which has a shape similar to that of a snail shell. The wheel must be driven at extremely high speed, either through gearing from the engine or by means of an exhaust turbine. The normal speeds for this type of supercharger range from 20,000 to 30,000 revolutions per minute. The centrifugal

force on the blower wheel is very high at such speeds, and it must be carefully made of the very best material. Forged aluminum alloy is usually used for this purpose. The casing is made of cast aluminum, and the shaft and gears of alloy steel of very great strength. Bearings may be either plain babbitt-lined bearings, or ball or roller bearings.

The *Roots-type supercharger*, shown diagrammatically in Fig. 108, is usually driven through gearing at from two to four times crankshaft speed. In construction and operation it is similar to a gear pump, each of whose gears, or *impellers*, has but two teeth. As the impellers revolve, they entrain air from the inlet and force it out of the discharge opening, thus building up a pressure on the discharge side. The impellers are aluminum or magnesium alloy castings, running in a cast aluminum alloy case. There must

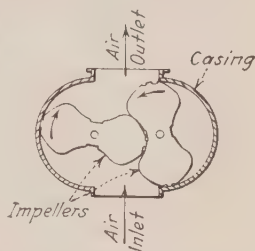


FIG. 108.—Roots-type supercharger. (Courtesy National Advisory Committee for Aeronautics.)

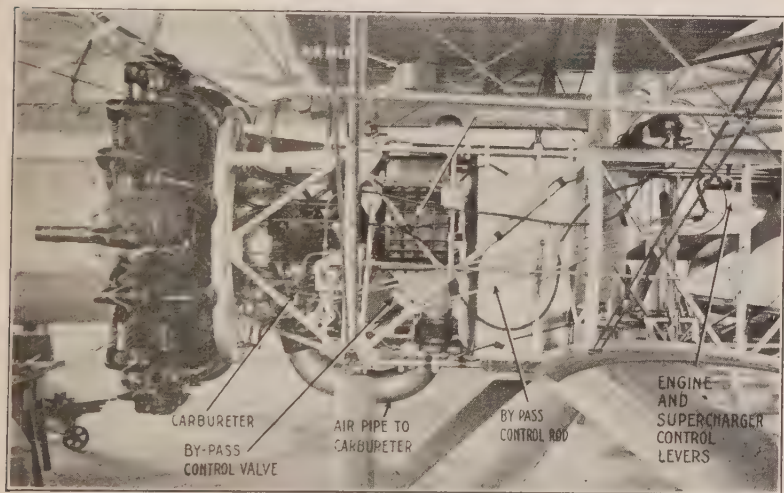


FIG. 109.—Roots-type supercharger installed in airplane. (Courtesy National Advisory Committee for Aeronautics.)

be a small clearance between the impellers and the casing, enough so that under the temperatures of operation the impellers will not expand far enough to strike the casing. The impellers

are geared together by steel spur gears, and the shaft and drive gears are also of steel. Ball or roller bearings are usually used for the impeller shafts. Figure 109 shows a typical installation of a Roots-type supercharger in an airplane.

Supercharger Drives.—In general, there are two distinct methods of driving the supercharger. One of these is to gear it directly to the crankshaft, in which case the speed of the supercharger is proportional to the engine speed. In the other, the supercharger is driven by a small exhaust-gas turbine.

Gear-driven Superchargers.—Gear-driven superchargers are driven by means of spur gears, the first gear of the group usually being connected to the rear end of the crankshaft. A single pair of gears may be used, as in the superchargers shown in Figs. 87 and 109. Where it is desired to have the blower shaft on the same axis as the crankshaft, a train of four spur gears is necessary. The gear shafts must be very accurately aligned and are generally mounted on ball bearings. On account of the high speeds at which they are required to run, the gears used to drive centrifugal superchargers must be of the hardest and strongest alloy steel available. Tremendous loads are imposed on the gears and drive shafts when the engine accelerates or decelerates, and shock-absorbing spring couplings are often used to reduce these loads to a minimum. In spite of all these precautions, however, the stresses are very high, so that the use of the gear drive is generally confined to the Roots-type supercharger, or to centrifugal superchargers having a relatively low critical altitude, less than 20,000 ft., and therefore a "low" maximum speed, say not over 20,000 r.p.m. The Pratt & Whitney engines and the Wright Cyclone, listed in Table III, have low altitude gear-driven superchargers mounted inside the crankcase at the rear.

The **exhaust turbine**, shown diagrammatically in Fig. 110, is used to drive centrifugal superchargers having a relatively high critical altitude (20,000 ft. and over). The turbine itself, which is mounted on the same shaft as the supercharger impeller, resembles a single-stage stream turbine. Since the exhaust gases from the engine to the turbine are very hot, the passages from the engine exhaust ports to the turbine nozzle, and the wheel and blades of the turbine must be made of an alloy steel which is extremely resistant to high temperature. Aluminum alloys

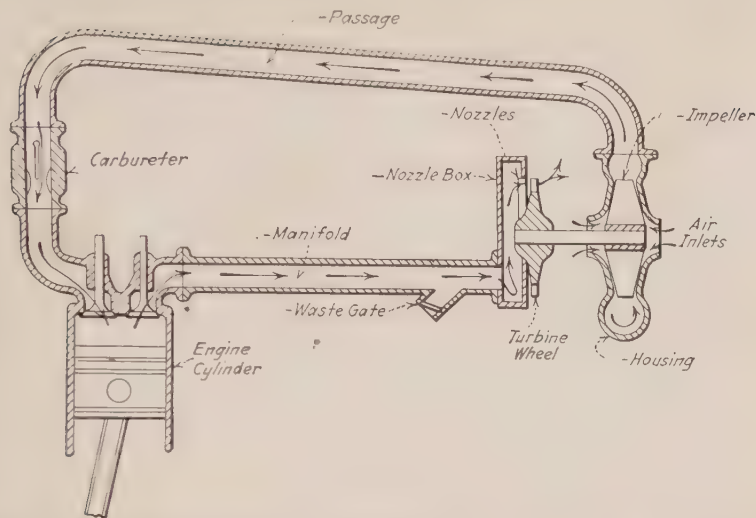


FIG. 110.—Operating diagram of exhaust-turbine-driven supercharger. (Courtesy Materiel Division, U. S. Army Air Corps.)

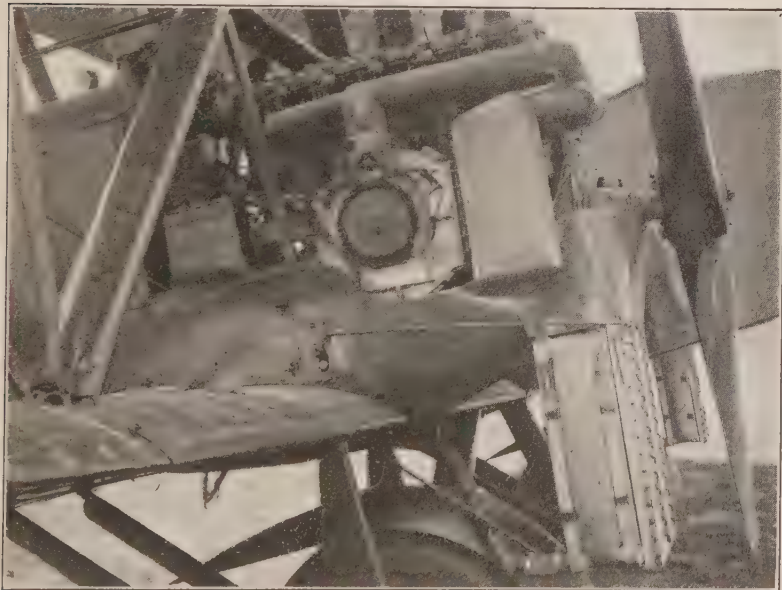


FIG. 111.—Exhaust-turbine-driven supercharger installed in airplane. (Courtesy Materiel Division, U. S. Army Air Corps, and General Electric Co.)

cannot be used where they are swept by the hot exhaust gases of an engine. The great advantage of the turbine drive, aside from the entire absence of gears, is that it permits the speed of the supercharger to be regulated more or less independently of the engine speed. Its great disadvantage is the presence of bulky exhaust pipes and passages which run at high temperatures. A typical installation of such a supercharger is shown in Fig. 111.

Power of Supercharged Engines.—With a geared supercharger, assuming that the supercharger is supplying air at sea-level density to the carbureter at any altitude below its critical altitude, the following factors tend to alter the power delivered by the engine as the airplane ascends: the change in the power absorbed by the supercharger, the change in speed of the propeller due to change in the density of the air, and the change in pressure of the air in the exhaust pipes. The power required by the supercharger increases up to the critical altitude, beyond which it decreases. The reduction in air density on the propeller, as the airplane ascends, causes the engine and propeller speeds to increase, which increases the engine power. The reduction in back pressure against the exhaust tends to increase the power of the engine considerably, so that, as a matter of fact, instead of remaining constant, the power of a supercharged engine equipped with a gear-driven supercharger actually increases up to its critical altitude, beyond which it decreases at the same rate as in the case of an unsupercharged engine. The dotted curve in Fig. 76 (p. 98) shows the full power *versus* altitude characteristics of an engine with a gear-driven supercharger whose critical altitude is 12,500 ft.

When an exhaust-turbine drive is used, no power is taken from the crankshaft, but the back pressure at the exhaust remains nearly constant at the normal sea-level value, up to the critical altitude. Thus the engine operates up to the critical altitude with sea-level pressure at both intake and exhaust. The resistance to rotation of the propeller, however, decreases with increasing altitude, so that the speed of the engine, and consequently the power delivered to the propeller, will increase. The curve of power against altitude for an exhaust-driven supercharger, therefore, is very much the same as the curve in Fig. 76, shown for a gear-driven supercharger. This curve assumes that the

engine is equipped with a constant-angle propeller. If means are provided for varying the angle of the propeller blades, the engine speed may be held constant.

Intercoolers.—Compressing the air by a supercharger increases its temperature considerably and it is sometimes desirable to cool this air, before it reaches the engine, by means of an *intercooler*. This usually takes the form of a series of small tubes forming the passage between the supercharger and the engine and exposed to the air of the propeller slip stream. The air pipe at the bottom of the supercharger in Fig. 109 has been replaced by an intercooler since the photograph was taken. The action of the intercooler is the same as that of a radiator except that the tubes contain air instead of water.

CHAPTER X

AIRPLANE PERFORMANCE

The value of an airplane as a vehicle depends on what it can do in the air with the load which it is intended to carry, and the object of every designer is to produce a machine whose accomplishments are the utmost that can be attained with the means at his disposal. To a certain extent, it is difficult to describe at all definitely the behavior of an airplane in flight; stability, controllability and maneuverability cannot easily be expressed in figures, and the reputation of an airplane in respect to these characteristics may depend largely upon pilots' opinions—often very diverse. Other characteristics, such as speed, may readily be given numerical values, and are grouped under the general term *performance*. The different items which enter into the "complete performance," and the units in which they are expressed, are as follows:

Maximum speed at sea level, and at various altitudes, in miles per hour.

Minimum speed at sea level, in miles per hour.

Rate of climb at sea level, and at various altitudes, in feet per minute.

Angle of climb, in degrees.

Time required to climb to various altitudes, in minutes.

Ceiling, the maximum attainable altitude, in feet.

Endurance, the maximum time during which the airplane can remain in the air, in hours.

Range, the maximum distance which the airplane can cover, in miles.

All these characteristics are directly dependent upon the total weight of the airplane, and a change in this weight affects every one. For this reason, no report of the performance of an airplane has any real meaning unless it states the weight of the airplane for which the performance is given. If the weight is

not specifically mentioned, it is understood to be that with the airplane carrying its normal, or advertised, load, and if this is not the case, the fact should be explicitly stated.

The performance of an airplane depends primarily upon two factors—the power required to drive it through the air, and the power available from the combination of engine and propeller. These two factors will now be considered in some detail.

Power Required.—For a given airplane, the power required in level flight depends upon the airplane speed. The speed determines the angle of attack, the angle determines the drag

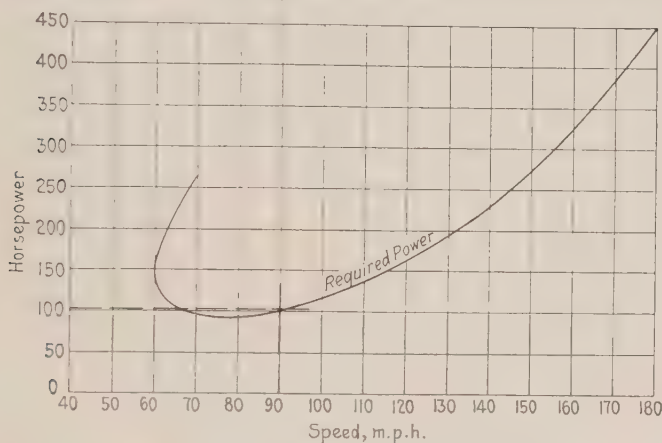


FIG. 112.—Power required at various speeds.

coefficient, and the drag coefficient, speed, and wing area together determine the drag due to the wings. The drag of the other parts of the airplane depends almost wholly upon the speed and upon the shape and area of the parts exposed to the wind. Both the wing drag and the parasite drag can be calculated by the engineer, and the total drag of the airplane found for any speed. If the total drag in pounds is multiplied by the speed in feet per second, and the product divided by 550, the result is the horsepower required to drive the airplane through the air. A typical curve of power required at various speeds is shown in Fig. 112.

The horizontal scale is one of airplane speeds, and the vertical scale gives horsepower required. From such a curve the power required for any airplane speed is easily found. A vertical

line, as shown in the figure, is drawn from a point on the horizontal scale corresponding to the desired speed, say, 90 miles per hour. From the point where this line intersects the curve a horizontal is drawn to the vertical scale, and is found to intersect it at a value of 102 hp., showing that this power is required to propel the airplane at 90 miles per hour.

An objection to the calculation of the drag of the whole airplane by adding together the drags of the individual parts is

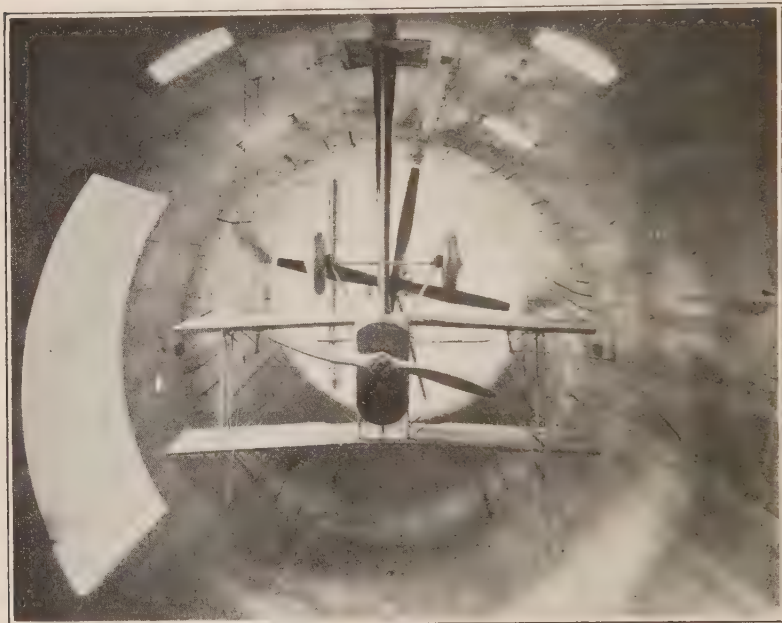


FIG. 113.—Airplane model in wind tunnel. (Courtesy Massachusetts Institute of Technology.)

that one part may affect the drag of another, so that the total resistance of several parts determined by testing them separately may not be the same as that of the same parts tested together. The drag of the complete airplane may, therefore, differ somewhat from that found by the summation method just described.

Instead of calculating the drag of each part of the airplane, the engineer may determine the total drag by testing a wind-tunnel model. This is a small reproduction of the airplane to scale, showing most of the important parts. It is supported in

a wind tunnel, a device which provides a stream of air moving uniformly at a known velocity. A wind-tunnel model ready for test is shown in Fig. 113.

By means of the balance on which the model is mounted, the lift and drag forces are measured for each angle of attack within the flying range. This procedure is essentially the same as that employed in testing model airfoils to determine their characteristics. From the results of such a test, it is comparatively easy for the engineer to calculate the drag, and, hence, the power required, for each airplane speed. This method has the advantage over that first described of allowing for the effect of one part on the resistance of another. The model test, however, is subject to errors of its own. The model cannot be an exact reproduction of the full-sized airplane on account of the impracticability of representing the small parts, such as wires and fittings, and even if it were geometrically similar to the large machine, its resistance would not be exactly proportional to its size. This last error is known as *scale effect*, and while an approximate allowance for it can be made by experienced aeronautical engineers, it is still a source of uncertainty.

The form of the curve shown in Fig. 112 is typical of that for an ordinary airplane. On account of the reversal of the curve at a speed of 60 miles per hour, there are two different values of power required for speeds slightly higher than this. Thus for 65 miles per hour the power required may be either 106 or 222 hp. The explanation of this phenomenon is the same as that for the two lift coefficients which correspond to angles of attack near the stalling speed. The point farthest to the left on the curve shows the lowest speed at which the airplane can fly. At this speed the angle of attack is that corresponding to the maximum lift coefficient. An increase in the angle leads to a reduction in the lift coefficient and so to an increase in speed, but at this higher angle the wing drag is considerably greater than it is when the airplane is flying at the same speed but below the stalling angle, so that the power required is higher, and this part of the curve lies above that corresponding to ordinary attitudes of flight. This upper part of the curve is really only of academic importance because under ordinary circumstances the airplane does not fly above the stalling angle.

The point farthest to the left on the curve is not the lowest point, a fact that indicates that the power required is not a minimum when the speed is a minimum. This results from the fact that the drag coefficient of the wing increases rapidly as the stalling angle is approached, and this increase in drag more than offsets the effect of decrease in speed, so that near minimum speed the power required increases instead of decreasing. Thus in the example given, the power required at minimum speed is 150 hp., while the minimum power required is 93 hp. at 77 miles per hour. As the airplane speed increases from that of minimum power, the power required increases, at first rather slowly, and then more rapidly, until toward the right end of the curve the rate of increase is so great that the power required goes up almost as the cube of the speed.

Power Available.—The power available for driving the airplane through the air depends upon two factors, the power output of the engine, and the propeller efficiency, for the power

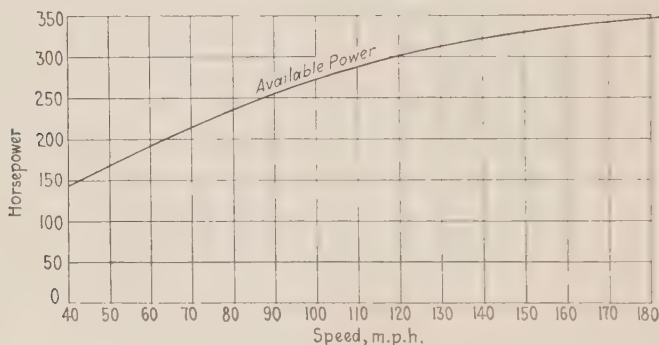


FIG. 114.—Power available at various speeds.

which does the driving is that actually delivered by the propeller. The relation between airplane speed and thrust power available is not a simple one, because a change in airplane speed involves not only a change in propeller efficiency, but also a change in engine speed. The propeller tends to slow down as the airplane speed decreases. The effect can, however, be estimated reasonably well from engine and propeller test data. The results of such an estimate of power available are shown in Fig. 114. This is a full-throttle curve, and is typical in being convex upward,

with its highest point at or near the right end. Such a curve is correct only for the engine, propeller and airplane for which it is drawn, and if either the engine or the propeller is changed to one of different design the form of the curve will be different. Any modification in the airplane which affects the action of the propeller will also change the curve.

Maximum Speed.—Let the curve of power available, and that of power required for the same airplane now be plotted together, as shown in Fig. 115. They intersect at the right at a point corresponding to an airplane speed of 162 miles per hour. This

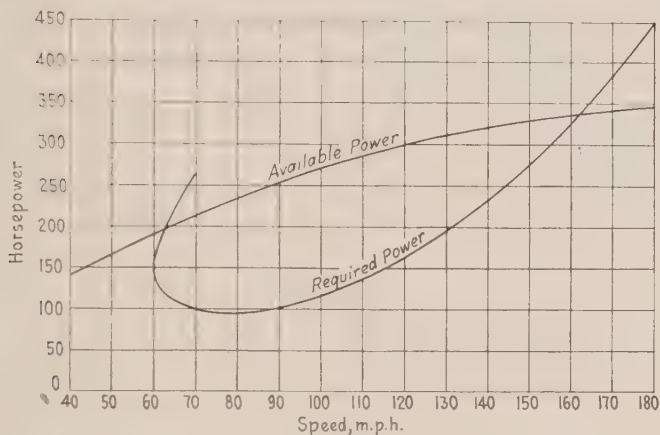


FIG. 115.—Power required and power available at various speeds.

intersection of the curves indicates that at this speed the power required to drive the airplane in level flight is exactly equal to that available. At 170 m.p.h., however, the power required is 385 hp., and that available is only 342 hp. It is thus evident that with this power plant the airplane cannot fly level at a speed greater than 162 m.p.h. The right-hand intersection of the two curves accordingly marks the maximum speed of the airplane in level flight.

Minimum Speed.—The curves of power available and power required intersect at the left at a second point corresponding to 62 m.p.h. In this case, however, the point of intersection has not so much practical significance, for it falls on the upper branch of the curve of power required, which corresponds to flight above

the stalling angle. The minimum speed of the airplane is then simply the point farthest to the left on the curve of power required, and in this case is 60 m.p.h. At this point there is still a margin of power, for that required is 150 hp., and that available is 190 hp. The airplane cannot fly slower than this minimum speed, however, because of the limitation imposed by the wing lift.

If the relations of the two curves are somewhat different, the case may be considerably altered. Suppose that the original power plant is replaced by a considerably smaller one, so that

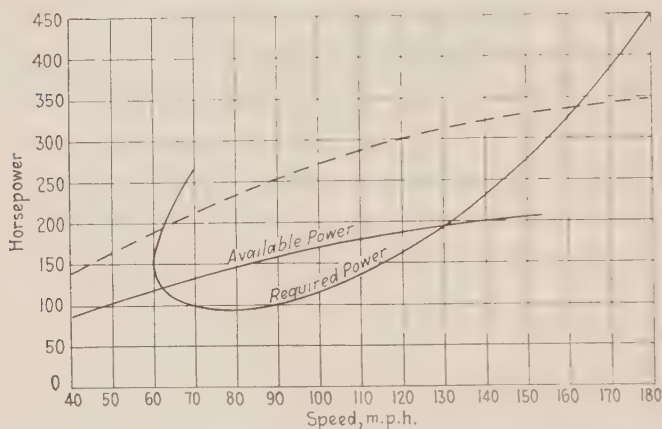


FIG. 116.—Effect of reduction in power available.

the curve of power available is as shown in Fig. 116. The power required is assumed to be the same as before, and the original curve of power available is shown dotted for comparison. The right-hand point of intersection of the two curves has moved considerably downward and to the left, and the maximum speed of the airplane is reduced to 130 m.p.h. The more striking change, however, is in the left-hand point of intersection, for this has moved from the upper to the lower branch of the power-required curve. It is now apparent that below a speed of 62 m.p.h., the power required to drive the airplane would be more than that available. For example, at 60 m.p.h. the power required is 150 hp., and that available is only 120 hp. The minimum speed is determined in this case, not by the limitations

of wing lift but by those of the power plant. This illustrates a general principle that if the engine power is too low, the minimum speed of the airplane may be increased.

Power and Speed Relations.—From Fig. 115, it is evident that at speeds between those corresponding to the two points of intersection the power available is more than that required. At 90 m.p.h., for example, the power required is 102 hp. and that available is 253 hp. The difference, 151 hp. is the *excess power*, and this excess power enables the airplane to climb. If the pilot wishes to fly in a level path at a speed less than the maximum, he must throttle the engine, because if he does not there is excess power, and the airplane will climb in spite of him.

Rate of Climb.—As the rate of climb of an airplane depends on the excess power, it will evidently be greatest at the speed where this excess power is greatest. The excess power is small at speeds near the minimum, and is of course zero at maximum speed. It usually is a maximum at a speed about equal to the minimum speed plus one third of the difference between minimum and maximum speed. Since, in climbing, the airplane is being lifted bodily as it moves along, it is easy to calculate the power needed in addition to that necessary for level flight. If C is the rate of climb in feet per minute (measured vertically, and not along the flight path) and W is the weight of the airplane in pounds, then the horsepower needed for climb is

$$\frac{CW}{33,000},$$

for it will be remembered that a horsepower is defined as that required to lift a weight of 33,000 lb. 1 ft. in a minute. From this the rate of climb may readily be calculated when the excess horsepower is known, for the equation may be written in the form,

$$C = \frac{33,000P}{W},$$

where P is the excess horsepower. In the example given (Fig. 115), the excess horsepower at 90 m.p.h. is 151. Then, if the weight of the airplane is 2,600 lb., the rate of climb at this speed is

$$\frac{33,000 \times 151}{2,600} = 1,920 \text{ ft. per minute.}$$

For the typical airplane which is being used as an example the greatest difference between power required and power available is 155 hp. at a speed of 100 m.p.h. The maximum rate of climb is then 1,970 ft. per minute and can be attained only at this speed. If the airplane speed is greater or less than this, the rate of climb is less than the maximum. This point is naturally of importance to the pilot who desires to make his airplane climb as rapidly as possible, so that in determining the climbing performance of an airplane tests are made at several different airplane speeds, and the final climb test is made at that forward speed which gives the best rate of climb.

It is evident from the equation that if the excess power remained constant, the rate of climb would vary inversely as the total weight of the airplane; so that if the weight of the airplane were doubled, the rate of climb at a given forward speed would be cut in half. Actually, the effect of increased weight is somewhat worse than this, for it increases the power required to maintain horizontal flight, and so diminishes the excess power. This involves a further reduction in climb.

Effect of Altitude on Performance.—In the preceding discussion of performance, it is assumed that the airplane is so near sea level that the air density is substantially constant. At the high altitudes reached by modern airplanes, however, the density of the air decreases so much as to have a marked effect upon the performance of the airplane.

Since the lift coefficient decreases with decreasing air density, it is necessary for an airplane to fly faster at a high altitude to maintain a given angle of attack than to maintain the same angle at a lower altitude. The ratio of lift to drag, however, is not changed, and the drag of the airplane for a given angle of attack is the same at all altitudes, so long as the flight path remains horizontal. The power required, however, is proportional to the product of drag multiplied by speed, so that the power required at a given angle of attack increases with altitude.

The effects can readily be calculated, and a new curve of power required can be drawn for any air density, that is, for any altitude, since the average variation of air density with altitude is well known. This procedure is illustrated in Fig. 117,

where curves of power required are given for the airplane already discussed, at altitudes of 0, 5,000, 10,000, and 15,000 ft.

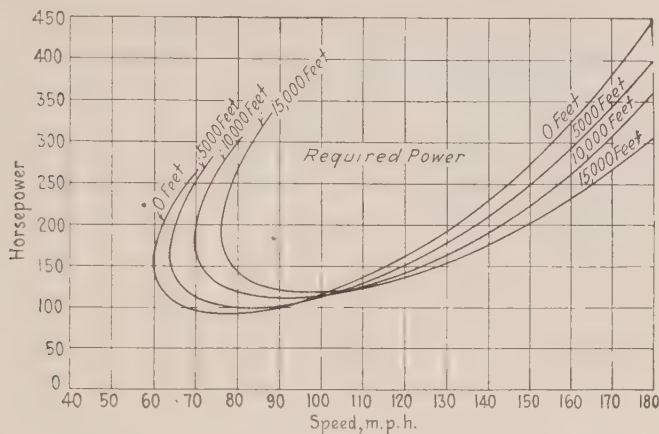


FIG. 117.—Effect of altitude on power required.

The effect of altitude on the power output of the engine has already been discussed in Chap. VII, and that on the propeller in Chap. VIII. The effect of altitude upon the combination of

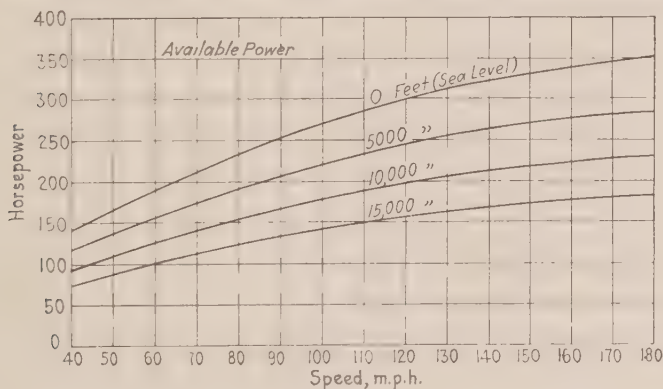


FIG. 118.—Effect of altitude on power available.

propeller and engine is not a very simple one, though it is familiar to aeronautical engineers. In Fig. 118, curves of power available are given for the airplane under discussion, at the same altitudes as those chosen for the curves of power required. The decrease

in power available with increasing altitude is quite evident.

The maximum speed, minimum speed, and rate of climb of the airplane at any altitude can be obtained from the pair of curves for that altitude in the same manner as the corresponding values for sea level conditions. Figure 119 shows the two curves for an altitude of 10,000 ft., with the corresponding curves for sea level dotted. It is apparent that the points of intersection of the 10,000-ft. curves are considerably closer together than those of the sea-level curves. The right-hand intersection has moved to the left, and the maximum speed is reduced from

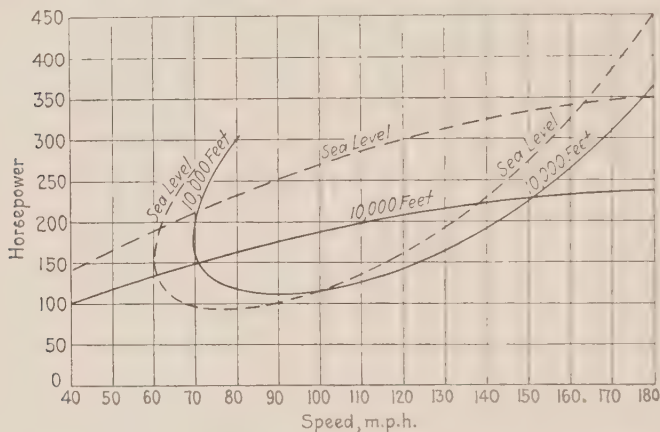


FIG. 119.—Effect of altitude on power available and power required.

162 to 151 m.p.h. The left-hand intersection of the curves is now to the right of the point of reversal in the power required curve, which indicates that there is not now power enough to enable the airplane to fly at the angle corresponding to its maximum lift coefficient; the minimum speed is increased from 60 to 71 m.p.h. The vertical distance between the two curves is considerably reduced, showing a decrease in the excess power and, consequently, in the rate of climb. At sea level, the maximum excess power and best climb were at an airplane speed of 100 m.p.h., while now the best climb is at 110 m.p.h. and has diminished from 1,970 to 920 ft. per minute.

This change in speed for best climb is another point of interest to the pilot who wishes to get the most out of his airplane. For

this reason, the preliminary test to discover the best rate of climb of the airplane must be run at several different altitudes, because the speed which is correct at one altitude is not correct at another.

Ceiling.—The pairs of curves in Fig. 120 show the effects of successive increases in altitude. The points of intersection of the power available and power required curves move closer and closer together until finally the two intersect at only one point and are tangent. Thus at an altitude of 20,000 ft., the maximum and minimum speeds are the same; the airplane can fly level at

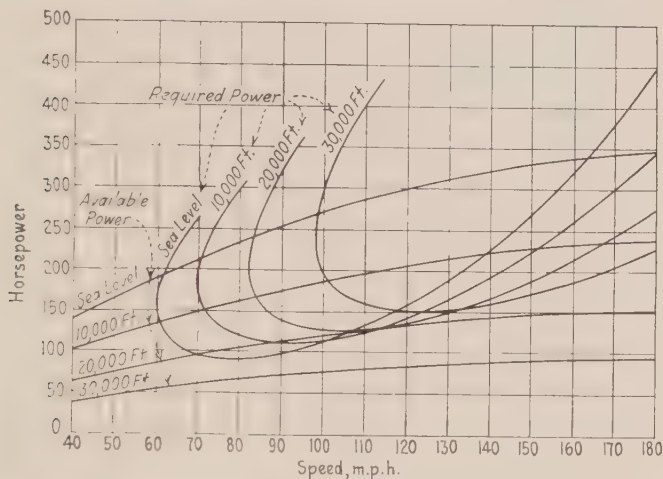


FIG. 120.—Power available and power required at various altitudes.

only one speed, there is no excess power at any speed, and consequently no further climb. This altitude is the *absolute ceiling*, and is evidently the greatest height which the airplane can attain under its own power. At any higher altitude, such as 30,000 ft. the power required is everywhere greater than the power available, and the airplane is consequently unable to maintain itself in a horizontal path.

By constructing pairs of curves, as shown in Fig. 120, the rate of climb can be found at as many altitudes as desired, and it is then possible to plot the curve in Fig. 121, which gives the maximum rate of climb at all altitudes. Distances representing altitudes are plotted on the vertical scale, and those representing

rates of climb are plotted horizontally. To find the rate of climb at 10,000 ft., for example, a horizontal line is drawn from the 10,000 point on the vertical scale, and from the point of intersection of this line with the curve, a vertical line is drawn which is found to intersect the horizontal scale at a value of 920 ft. per minute. The rate of climb of the given airplane is then 920 ft. per minute at 10,000 ft.

As it requires a considerable time for the airplane to reach the absolute ceiling, it has become customary to use as a basis

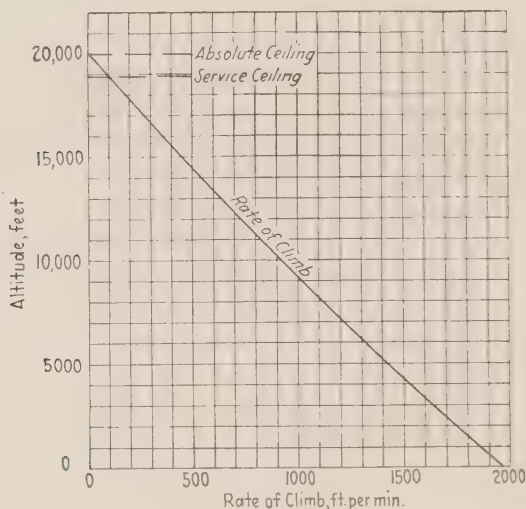


FIG. 121.—Maximum rate of climb at various altitudes.

of comparison the altitude at which the rate of climb has fallen to 100 ft. per minute. This is called the *service ceiling*, and really indicates the practical, though not the theoretical limit, to the climb of the airplane. The service ceiling is indicated in Fig. 121, and it will be noted that at this point the rate of climb is 100 ft. per minute.

From the curves in Fig. 120, the maximum and minimum speeds of the airplane for various altitudes can also be found, and so curves can be plotted to show maximum and minimum speeds at all altitudes, as shown in Fig. 122. The two curves

evidently intersect at the absolute ceiling, where the maximum and minimum speeds are the same.

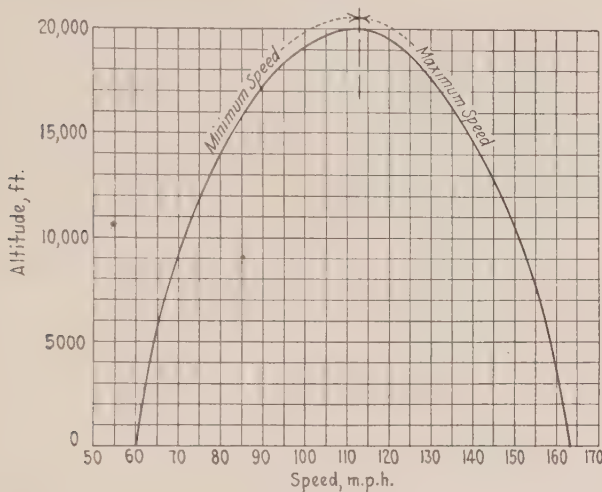


FIG. 122.—Maximum and minimum speeds at various altitudes.

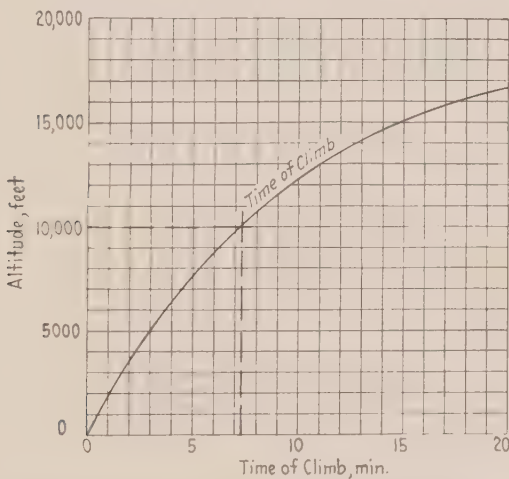


FIG. 123.—Time of climb to various altitudes.

Time of Climb.—Since the rate of climb can be found at each altitude, it is possible to calculate also the time required for the airplane to climb to any given altitude. The results of a

series of such calculations are most conveniently shown by a curve like that in Fig. 123, which gives the time required to climb to any altitude. For the airplane under consideration, the curve indicates a climb to 10,000 ft. in 7.3 min.

The performance of an airplane is often summarized in a group of four curves of maximum speed, minimum speed, rate of climb, and time of climb, all plotted on a common vertical scale of altitude. Those for the airplane which has been used as an example are shown in Fig. 124. These four curves, if accom-

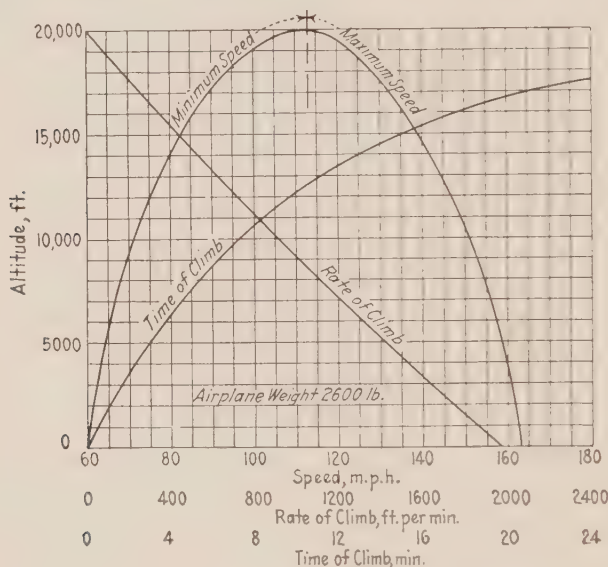


FIG. 124.—Performance at various altitudes.

panied by a statement of weight, ordinarily give the essential information desired about the performance of an airplane.

Angle of Climb.—The ability of an airplane to clear obstructions surrounding the field from which it takes off depends not upon the rate of climb, but upon the slope of its flight path. A machine may have a high rate of climb, but at so high a forward speed that the obstacle is reached before altitude enough to clear it is gained.

The important forces acting on an airplane which is flying in an upwardly sloping path are shown diagrammatically in Fig.

125. The weight W of the airplane which acts vertically downward, may be resolved into two components, one W_L perpendicular, and the other W_D parallel to the flight path. The first is balanced by the lift L , and the other is added to the airplane drag D and must be balanced by the propeller thrust T . The part of the propeller thrust which balances the drag is that required for horizontal flight, and the difference between this and the total thrust, that is, the *excess thrust*, determines the angle of the

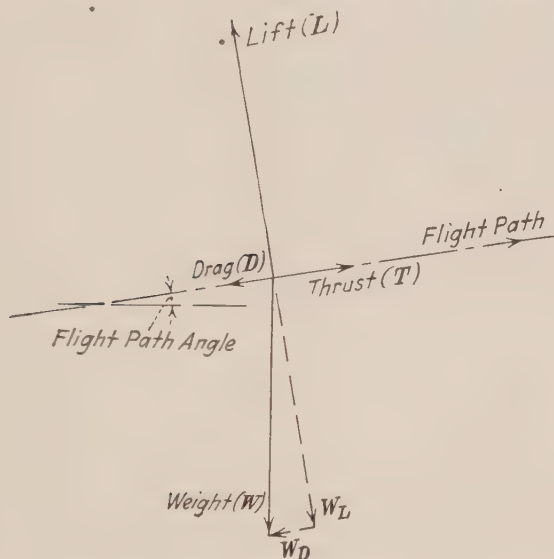


FIG. 125.—Forces acting on airplane in climb.

flight path, for it is evident that the steeper the path, the greater the value of W_D to be balanced.

Curves of thrust required for horizontal flight at various speeds, and of thrust available from the propeller may be drawn, as shown in Fig. 126, from the data used in obtaining the curves of power required and power available. The excess thrust at any speed is represented by the vertical distance between the two curves. From the excess thrust the angle of climb may easily be calculated by trigonometry on the basis of the diagram in Fig. 125. The process of finding excess thrust is like that of

finding excess power, except that *forces* and not *rates of doing work* are being considered.

The speed of maximum excess thrust is evidently that of best angle of climb, and the process of finding it can evidently be repeated at any desired altitude. It is thus possible to plot the best angle of climb and the speed corresponding to it for all altitudes.

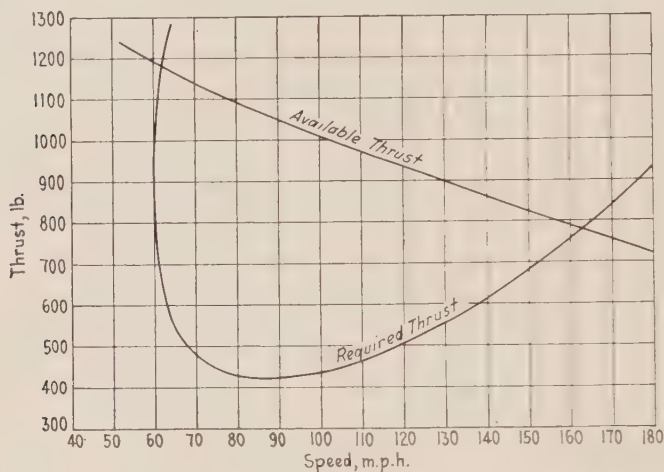


FIG. 126.—Thrust available and thrust required at various speeds.

Range and Endurance.—By *range* is meant the distance which can be covered by an airplane in a single flight; the *endurance* is the time during which an airplane can remain in the air, without reference to the distance covered. In the absence of a statement to the contrary, it is always understood that the flight is accomplished without landing or replenishment of fuel.

The problem of endurance is somewhat the simpler of the two. The endurance is greatest at the speed of least fuel consumption per hour. This speed is not the minimum flying speed, nor is it usually the speed of minimum power required. It has already been mentioned that the propeller efficiency tends to fall off with decreasing airplane speed, and also with decreasing engine speed, and it has likewise been pointed out that the efficiency of the engine decreases with decreasing revolutions per minute and power output. In calculating the endurance of an airplane, therefore,

it is necessary to find power required, engine speed, propeller efficiency, and specific fuel consumption of the engine for the different speeds of flight. From this information, a curve can be plotted showing the pounds of fuel consumed per hour for all flight speeds. Such a curve is shown in Fig. 127; it has a

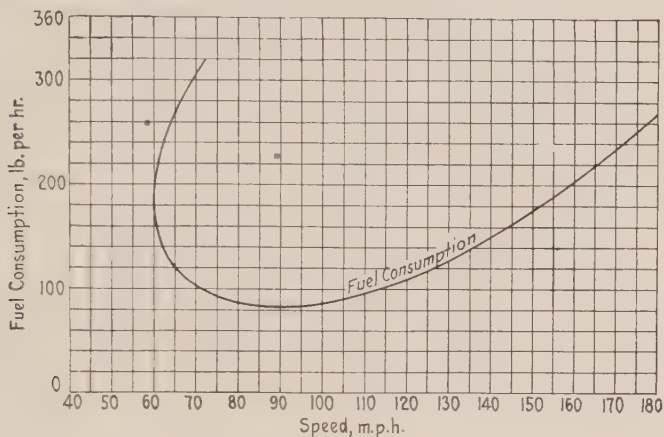


FIG. 127.—Fuel consumption at various speeds.

minimum value at 92 m.p.h., where the fuel consumption is 83 lb. per hour. This, therefore, is the speed at which the airplane should fly in order that it may remain in the air for the longest possible time on a given quantity of fuel. One such curve, however, is not enough if the weight of fuel carried is large in

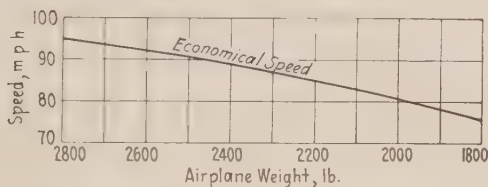


FIG. 128.—Most economical speed for various weights of an airplane.

relation to that of the airplane, for as the total weight of the airplane decreases so does the power required. It is, therefore, necessary to draw a curve for each of several different airplane weights, from the initial weight fully loaded down to the final one with practically all the fuel exhausted. When these curves have been constructed, and the flight speed for least fuel consumption

at each airplane weight determined, a second curve is drawn, as in Fig. 128, to show the most economical speed for each airplane weight during the flight, or better, as in Fig. 129, for various quantities of fuel in the tanks. A pilot of an endurance flight can observe his fuel quantity gage and be guided by the curve as to the best speed at which to fly at all times. Unfortunately, this correct speed is often so low as to make control of the airplane

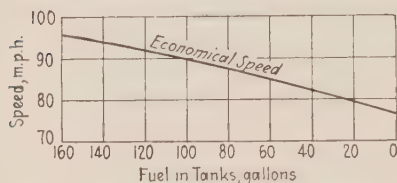


FIG. 129.—Most economical speed for various quantities of fuel remaining in tanks.

difficult, particularly with the heavy weight at the start of the flight, so that the pilot may have to fly somewhat faster.

If the quantity of fuel carried is increased without a corresponding decrease in some other weight, the additional endurance must evidently be calculated on the basis of the fuel consumption at the beginning of the flight, not on the average nor on that at the end. Wind makes no difference unless it is so violent or so irregular as to cause difficulty in control.

Range depends, not on fuel consumption per hour, but on fuel consumption per mile. By methods much like those used for determining the endurance curves, it is possible to construct curves for various total airplane weights which show the weight of fuel consumed per mile at different speeds. From a series of these curves, one giving the least possible fuel consumption per mile for different airplane weights can be drawn, together with one showing the airplane speed at each weight for maximum range. Both long range and long endurance flights must obviously be made with the engine throttled, except possibly at the start.

In long-range flights, wind velocity and direction make a very appreciable difference both in the distance which can be covered and in the speed at which the airplane should be flown. The range is evidently reduced by a head wind, and increased by a tail wind. The airplane is flown more slowly in a following wind so as to obtain more benefit from it, but in a head wind, the air speed is increased so to reduce the time during which the airplane is being held back.

Performance Testing.—It might be inferred from the preceding discussion of curves and other rather theoretical matters that the determination of airplane performance is chiefly a matter of calculation. This is by no means the case, and under most conditions the best means of determining performance is by testing the airplane in flight under known conditions. Performance testing, however, is not easy and not every pilot does it well. At best, the process is not as accurate as might be desired, and if it is carelessly carried out the results may be very far from the truth.

The easiest airplane characteristic to determine by test is maximum speed at sea level. This involves only a determination of the time necessary for the airplane to fly over a measured course laid out on the level ground. To eliminate the effect of wind, the speed is ordinarily taken as the average of that on four runs, two in each direction. Great care in timing is essential, for, ordinarily, the airplane speed is so high in proportion to the length of the course that even a very small error in starting or stopping the watch makes a very appreciable difference in the apparent speed of the airplane. The practice of announcing airplane speeds in races in hundredths or thousandths of a mile per hour is absurd. A determination correct to the nearest mile per hour is good, and further places of decimals are merely an overemphasis of arithmetic.

Evidently, the airplane must fly level while the time is being observed, for if it flies down hill the true speed is exaggerated, as it is also if the airplane dives just as it enters the course. A cross-wind reduces the apparent speed, because it carries the airplane off somewhat to the side and so requires it to fly a greater distance through the air than that which it covers over the ground. This error, however, is rather less than is commonly supposed. If, for example, the wind is blowing at right angles to the course with a speed one-tenth that of the airplane, the apparent airplane speed is only $\frac{1}{2}$ per cent less than the true speed.

For determining the speed in ordinary flight, the airplane is usually provided with an airspeed indicator, such as is described in Chap. XVII. This instrument is not considered accurate enough for use in test flights until it has been calibrated, that is,

until its errors have been found by comparing its indicated speeds with those calculated by timing the machine over a measured course.

Minimum speed would be just as easily determined as maximum speed were it not for the fact that most airplanes when flying near the stalling angle are not especially easy to control. In order that the times may be taken accurately it is necessary for the airplane to fly at a height of not much more than 100 ft., and under these conditions there is no opportunity for recovery from a temporary loss of control. The lowest speed which the pilot considers safe may therefore be somewhat above the true minimum speed of the airplane. There are other methods for determining minimum speed, but they are indirect, and require tests with special instruments. The ordinary air-speed indicator is not very reliable at low speeds. The estimate of an observer who, without instruments, watches the airplane as it comes in to land, is even less reliable.

The ratio of maximum speed to minimum speed is a good indication of the speed qualities of an airplane. Machines of clean design with large engines in proportion to their size, such as racers and pursuit airplanes, often have a maximum speed three times the minimum, or, to use the technical expression, a *speed range* of 3. If the engine power is reduced, or if projections or irregularities in airplane form add resistance, the speed range is less. In low-powered commercial airplanes, for example, it is not likely to be much greater than 2. In judging claims of airplane performance, it is well to determine the speed range. A very high value is reasonable only with an abnormally large engine, or an unusually clean airplane design. If there appears to be no good reason for a high speed range, the chances are that the minimum speed has been underestimated.

Rate of climb is found by keeping a record of the time required to attain different altitudes. Such a determination may not be extremely accurate even under the best conditions, on account of instrument errors, atmospheric irregularities, and variations in engine performance. Speeds at altitudes much above the ground must ordinarily be determined from a calibrated airspeed meter, with the altimeter reading held constant to make sure that the airplane is being flown in a horizontal path. A test to

determine the ceiling of an airplane is a particularly difficult one, because when the rate of climb has become small, the effect of atmospheric irregularities is relatively large. Some authorities believe that even good determinations of airplane ceiling by flight tests may be in error by as much as 10 per cent. There is no justification for quoting figures for altitude performance to a high degree of refinement.

Complete tests to determine endurance and range are seldom made except as incidental to attempts to break records. It is possible, however, to check calculated curves by making relatively short flights. An airplane may be flown at a definite weight for an hour or two, and the fuel consumption determined. Such a test gives a check of one part of an endurance curve, and if these short test flights are made at several different airplane weights, the curve may be verified at several points along its length, so that errors in the calculations may be corrected. Similar test flights between two points only a moderate distance apart may be made to verify curves of range. Here, however, the effect of wind is troublesome, and may reduce the accuracy of the results.

Weather conditions, particularly those of temperature and barometer, have a marked influence upon the performance of an airplane. High pressure and low temperature, for example, both tend to increase the air density, and so improve both climb and speed. It is customary therefore, not to quote the actual results, but to calculate from them what the machine would have done if the atmospheric conditions had been average. Obviously a fair comparison of the performances of different airplanes can be made only if they are all reduced to standard average conditions.

Factors Affecting Performance.—While the performance of an airplane is affected directly or indirectly by almost everything about the machine, four principal characteristics largely determine it. These are weight, wing area, power, and fineness. Fineness expresses the extent to which the external shape of the airplane approaches the streamline form. A machine with a good fineness is one designed to cause little disturbance to the normal streamline flow of the air. Racing airplanes exemplify good fineness, and some of the older machines, with forests of

struts and wires exposed to the wind, illustrate what is meant by poor fineness.

The effects of weight, wing area, and engine power are usually discussed in terms of two ratios. One is *wing loading*, the quotient of total airplane weight divided by wing area, and the other is *power loading*, the quotient of total airplane weight divided by rated engine power. The fundamental equation of lift (p. 24) shows that wing loading determines minimum speed and that with a given airfoil the minimum speed varies directly as the square root of the wing loading. If the wing loading, therefore, is increased by 25 per cent, the landing speed or stalling speed is increased by 12 per cent.

In the design of an airplane, the stalling speed is usually limited in advance, so that once the airfoil has been chosen the wing loading is fixed, since the choice of airfoil involves a definite value for the maximum lift coefficient. For ease and safety of landing it is, of course, desirable that the minimum speed should be low, which means that the wing loading should be low. A low wing loading necessarily involves a large area, with a consequent increase in wing drag, and decrease in maximum speed. Small changes in wing loading do not have much effect upon the speed range, so that it is quite easy to tell approximately how much the maximum speed is reduced by a given reduction in landing speed. Suppose, for example, that an airplane is designed to have a minimum speed of 60 m.p.h., and that with the wing area necessary for this the high speed is 150 m.p.h.; the speed range is then $2\frac{1}{2}$. If now the wing loading is decreased by increasing the area enough to bring the landing speed down to 56 m.p.h., the maximum speed will be only 140 m.p.h.

Wing loading affects also the performance of the airplane at altitude, and if this loading is increased without changes in other characteristics the climb and the speed at high altitude are reduced. In a racing machine, which flies only at low altitudes, this would not matter, but in a pursuit airplane, which does most of its flying at high altitudes, the effect is serious. A comparison of two pursuit machines based entirely on their relative speeds at sea level might therefore be misleading, for the superior machine at low altitude might be the inferior, both in speed and climb, at the fighting altitude.

Power loading has an even greater effect than wing loading on the performance of an airplane, except, as already explained, on minimum speed. It is quite obvious that the lower the power loading, that is, the greater the engine power in proportion to the weight of the airplane, the higher will be the speed and climb. Figure 130 shows the power-required curve for a certain airplane, together with power-available curves for several different power loadings. The increase in speed obtained from an increase in power is, as usual, rather disappointing, since an

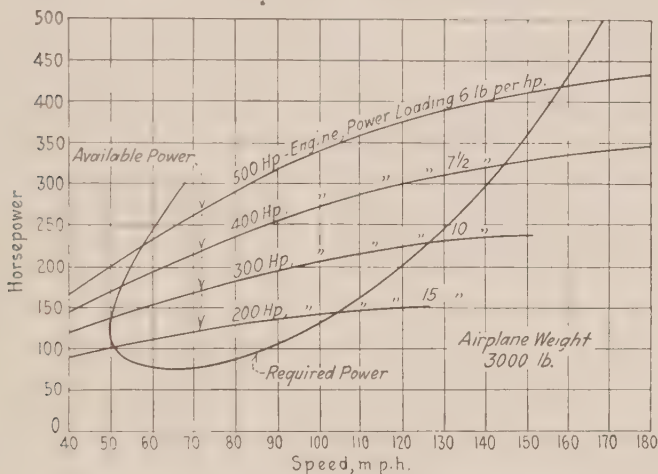


FIG. 130.—Effect of changes in power loading.

increase in engine power from 200 to 300 hp. involves an increase in high speed only from 104 to 128 m.p.h. The effect of power loading upon rate of climb is much greater; in this case, for example, an increase in engine power from 200 to 300 hp. leads to an increase in excess power from 42 to 92 hp., or 119 per cent. A 50 per cent increase in engine power thus gives a 119 per cent increase in rate of climb. These results are correct, however, only as long as the total weight of the airplane is unchanged. As it is ordinarily possible to increase the engine power only by increasing the total weight of the airplane, or by decreasing the margin of weight available for pay load, the advisability of an increase in engine power for a given airplane is a rather com-

plicated question, and can be decided only after a careful consideration of all the effects involved in the change.

The effects of fineness upon performance are perfectly evident, but not easily expressed in figures. If the fineness of the airplane is improved, its resistance is decreased, so that the power required is less at every speed. Consequently, with a given power available, the performance is improved in every respect.

The fineness of an airplane depends upon wing drag as well as upon parasite drag. A thin wing usually has a lower minimum drag than a thick one, but its lift coefficient may be so much lower that the wing loading has to be materially reduced to avoid an increase in the landing speed. Such a decrease in wing loading involves an increase in area, with consequent greater structural weight and wing drag. The choice of the best airfoil for a particular airplane thus becomes a matter of some difficulty, and cannot be made intelligently without a thorough study of the problem from all angles. Certain airfoils are better for certain kinds of airplanes, and others for other kinds, but as yet there is no one best airfoil. On the one hand, it might seem desirable to use a very thick wing, strong enough to require no external bracing, and so to reduce the parasite resistance. The use of a thick wing, however, might lead to such an increase in wing drag as to impair the overall fineness instead of improving it. On the other hand, if a thin wing is used, the additional external bracing required may involve so much added resistance as to have an unfavorable effect on the fineness of the airplane as a whole. In most cases a compromise of some sort must be made.

An examination of a number of airplanes of about equal size and power, designed for the same service, shows only a small variation in type of airfoils used. Several may use identical airfoils. So much work has been done in the development of airfoils, and the results are so well known, that among conventional modern airfoils of equal maximum thickness there is not a very great variation in lift and drag coefficients, or in L/D ratio. If, therefore, two airplanes of about the same power and weight differ appreciably in performance the explanation is likely to lie in the relative arrangement of the various parts, and in the care employed in eliminating unnecessary resistances.

The propeller is comparatively so small a part of the airplane that its importance in determining performance is often overlooked. Actually, the importance of propeller efficiency is very great. If under certain conditions the propeller on a 400-hp. engine has an efficiency of 80 per cent, the thrust horsepower is 320 hp., but if because of a poor choice of propeller the efficiency is only 70 per cent, a perfectly reasonable assumption, the useful output of the propeller is only 280 hp. There is, then, a loss of 40 hp. in power available, and a material reduction both in speed and in climb.

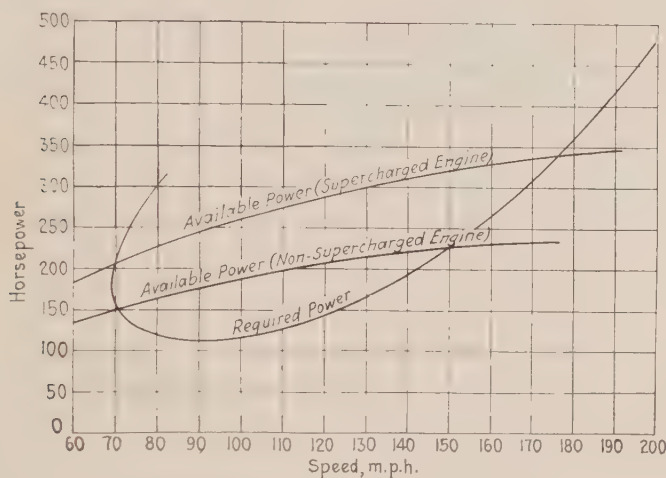


FIG. 131.—Effect of supercharging on power available at 10,000 ft.

The effect of supercharging on the performance of an airplane at altitude is very marked indeed. A typical illustration of this is given in Fig. 131, which shows curves of power available at 10,000 ft. with and without supercharging. The curve of power required at this altitude is also drawn. Supercharging increases the maximum speed from 150 to 176 m.p.h., and the rate of climb from 925 to 1,850 ft. per minute. Since supercharging tends to reduce the power output of the engine at low altitudes, the performance of the supercharged airplane near the ground is often inferior to that of the conventional machine. Figure 132 shows curves of maximum speed, minimum speed, rate of climb, and time of climb at various altitudes for the airplane with a

conventional engine, and for the same machine with an engine supercharged to 10,000 ft. The losses in performance at low altitudes, and the very marked gains at higher ones, are evident. A little consideration will show also that since with the same engine power the speed of the supercharged machine at altitude is

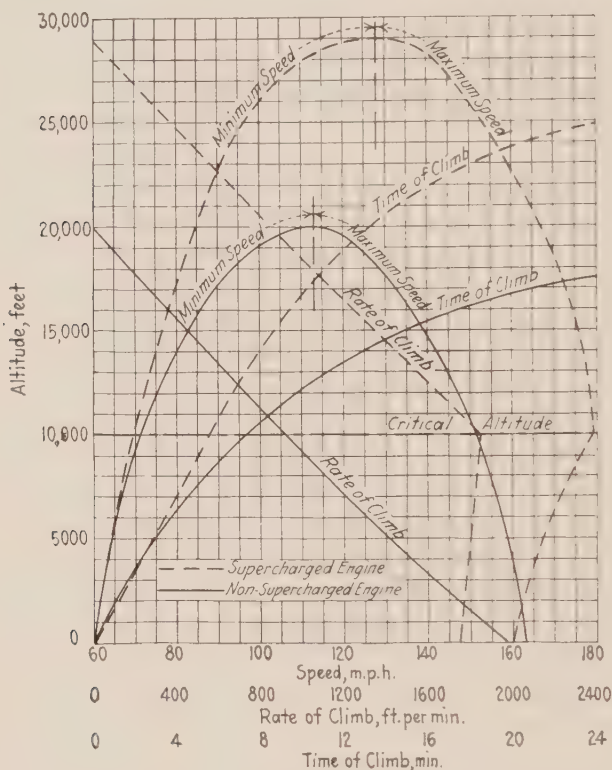


FIG. 132.—Effect of supercharging on airplane performance.

greater than that of the conventional one at sea level, its range at full speed with a given quantity of fuel is also increased.

While military pursuit airplanes and special machines designed especially for flight at high altitudes have thus far been almost alone in using supercharged engines, it is likely that the future will see fast commercial transport airplanes equipped in this way and flying at high altitudes.

CHAPTER XI

AIRPLANE MANEUVERS

The art of controlling an airplane is not to be discovered in a book, nor can anyone expect to learn how to fly by any means other than actually doing it. It is quite possible, moreover, for a person to learn to fly with very little knowledge of the principles on which the airplane and its engine operate, just as many people drive automobiles for years with little or no idea of what goes on under the hood. Both automobile driver and airplane pilot, however, are likely to be better operators of their vehicles if they understand the natural laws to which they must conform. Complicated airplane maneuvers are hard to describe and still more difficult to understand; the simpler ones are more easily dealt with in theory as well as in practice, and some of them will now be considered.

Straight Flight.—If the airplane is flying in smooth, undisturbed air, the pilot has very little to do, and this sort of flight is hardly to be considered as a maneuver at all. A well-designed airplane in good condition will tend to fly straight, except for the effect of the propeller slip stream upon the rudder. As has already been mentioned, the slip stream from a right-hand propeller rotates in a clockwise direction as seen from the rear, so that it strikes somewhat on the left side of the rudder and fin, since most of the area of these surfaces is usually above the thrust line. Thus it tends to push them toward the right, an action which would turn the airplane to the left, so that to maintain a straight course the rudder must be turned in the opposite direction, that is, to the right. The amount of right rudder necessary obviously depends upon the engine speed, which determines the slip-stream velocity. Some machines are now fitted with an adjustable fin which can be set at an angle to counteract this slip-stream effect, relieving the pilot of the necessity of applying a constant force on the rudder pedals.

If the airplane is nose heavy or tail heavy the pilot must maintain a steady pressure on the stick to prevent the airplane from diving or climbing. This condition may be corrected by an adjustable stabilizer. A "wing heaviness," or lack of lateral balance, must be compensated for by use of the ailerons.

In slightly disturbed air, a stable machine may still fly without much attention from the pilot, for it will tend to return to its original attitude after the disturbance has passed. If the disturbances are violent or continuous, the recovery of the airplane may be too slow, and in order to check wide departures from the desired attitude and course, the pilot may have to intervene with the controls.

Turns.—The ordinary turn in a horizontal plane is a comparatively simple matter, for when the rudder is put to one side or the other, the airplane will begin to turn, and will continue turning as long as the rudder is held over. If the machine has proper lateral stability, it will automatically take the correct angle of bank, so that it neither skids outward nor slips inward. Sometimes, however, the ailerons must be used to assist the natural tendency to bank. The common difficulty is that the roll may not stop when the correct angle of bank has been reached, on account of the higher speed and consequent greater lift of the outer wing. Under these conditions, the pilot gives opposite aileron, that is, he lowers the aileron on the inside wing and raises that on the outside, thus holding the angle of bank constant.

In an airplane with a reasonable reserve of power, it is possible to shorten the radius of turn and finally to increase the angle of bank to 90° , so that the wings are vertical. Under these conditions, the effect of rudder and elevator are interchanged; the latter controls the turn, and the former determines the attitude of the machine to the horizontal. For this reason, the maneuver is often called a "flipper turn." The shortness of the turn which can be executed depends upon the size and effectiveness of the horizontal tail surfaces in turning the airplane, and also upon the wing loading. When the airplane turns, the wings must exert a centripetal force, that is, an extra lift acting inward toward the center to hold the machine in the curved path. Since with a given airplane speed the centripetal force necessary varies inversely as the radius of the turn, the sharper the turn the

higher the centripetal force. If the wing loading is high, the wings cannot exert enough centripetal force to hold the machine in a sharp turn, so that it "squashes," that is, moves bodily outward from the center of the circle, even though the angle of attack is that of maximum lift. When the airplane is banked at 90° , it naturally loses altitude, because the lift produced by the side of the fuselage is comparatively small.

In making a turn, particularly with a low-powered airplane, it is important for the pilot to make sure that he is not holding the nose up too high, and so getting the airplane into a stalling attitude without realizing it. A stall in a turn is very likely to result in a spin, and if this occurs at a low altitude, the consequences may be very serious. As more power is needed for flight in a curved path than in a straight one, only an airplane with a good reserve of power can safely attempt a climbing turn.

Glide and Dive.—If while the airplane is flying in a level path the stick is pushed forward, the increased lift on the tail surfaces which results from turning the elevators down raises the tail and turns the nose of the airplane down. With the airplane now upon a path inclined downward, part of the weight acts along the path and enables the speed to be maintained with the engine throttled, or even stopped entirely. This maneuver is called a *glide*. As already mentioned in the chapter on stability, a stable airplane will stay naturally in a glide just steep enough to maintain the trimming speed, so that the control stick need not be held forward unless the speed desired is higher than this. If there is sufficient altitude, the glide may be made progressively steeper until finally the flight path is vertical and the glide becomes a *dive*. The speed will then increase until it reaches a value at which the resistance of the airplane is equal to its weight. This equilibrium speed, which is called the *terminal velocity*, is much higher than the maximum speed in horizontal flight. In a *terminal dive*, one in which the speed has reached the terminal velocity, the engine must be throttled, for otherwise it may turn at a speed high enough to wreck itself though not high enough to give any appreciable propeller thrust. In fact, even with the throttle closed, the engine is likely to turn much faster than its rated speed, since the propeller acts as a windmill.

Recovery from a dive is accomplished by pulling back on the stick, so that the resulting force on the stabilizer and elevator acts to increase the angle of attack of the wings, increasing their lift, and curving the flight path upward. This maneuver, which is called a *pull-out*, may impose very high stresses upon the airplane, because the lift coefficient may be a maximum at the same time that the speed is very much above the maximum speed in horizontal flight. Under these conditions, the lift on the wings may be momentarily eight or even ten times the weight of the airplane. Only pursuit airplanes ordinarily have wings designed to withstand the stresses in a pull-out from a terminal dive with the stick held all the way back. Other airplanes must be pulled out more gently, lest the wings collapse under the load.

Landing.—In theory, landing an airplane is not a difficult maneuver. It consists of a glide at moderate speed to within a short distance of the ground, followed by a level flight just above the field with the engine idling. As the speed decreases, the angle of attack is increased so that the machine is held off the ground until the speed has reached the minimum at which flight can be maintained. Finally, the airplane settles to the ground, and rolls until it comes to a stop. If there is plenty of room, the pilot may not attempt to hold the machine off until the last possible moment, but let the wheels touch first, making a *two-point* landing. If wheels and tail skid touch simultaneously, a *three-point* landing results. The practical difficulty in the maneuver lies in the necessity of close timing and accurate judgment of distance. If the machine is leveled off too high, the result is a *pancake landing*, a sharp drop of several feet when the stalling speed is reached. Slowness in leveling off leads to a hard impact against the ground, with bouncing or damage to the landing gear. If the glide is begun too far from the field, the airplane will be close to the ground and losing flying speed before a place suitable for landing is reached, while if the glide starts too near the field, the machine cannot be stopped until the landing area has been passed. A landing is always made into the wind if possible, so that for a given minimum air speed the ground speed may be least.

Take-off.—In taking off, the throttle is opened wide at the start, and as soon as there is enough speed the tail is lifted by the

use of the elevators, so that the airplane runs along the ground on its wheels at an angle which gives low wing resistance. When flying speed is attained the stick is pulled back, thus depressing the tail again and increasing the angle of attack of the wings, and the machine lifts off. If plenty of room is available, the machine may be allowed to run until it lifts off naturally, without much increase in angle of attack. Normally, a take-off is made into the wind so that flying speed relative to the air may be attained at the lowest possible ground speed.

Loop.—A loop may be regarded simply as a turn executed in a vertical plane. The pilot pulls back on the stick, and so raises the elevator, causing a greatly increased download on the tail. This starts the airplane rotating about its center of gravity, and at the same time gives an increased lift which curves the flight path upward. If the speed is high enough, and the controls are sufficiently powerful, the rotation may be made to continue long enough to carry the airplane around a complete circle before flying speed is lost. Very often the loop is preceded by a steep glide to gain speed. If the engine power is low, the controls inadequate, or the pilot unskilful, the machine is likely to lose flying speed and “hang” at the top of the loop, so that instead of completing the evolution it “falls off,” that is, slides off to the side.

The “outside” loop is executed by nosing down into a vertical dive and then going on over backward and up to a level position again. The loop takes place below the point at which the maneuver is started, and the top of the machine is to the outside of the curve. Since the maximum lift of the wings inverted is much less than that which they can exert when right side up, it is very difficult to complete the second half of the outside loop, and the maneuver has been performed only by a very few pilots. In the ordinary loop the centrifugal force holds the pilot in his seat, but in the outside loop it tends to throw him out, and while his belt prevents this, the effects of a large force directed toward his head may be very unpleasant.

Inverted Flight.—It is possible for an expert pilot, if he is firmly secured in his seat, to fly an airplane upside down for some distance, though the lift of the wings in this position is usually not enough to enable the flight path to be kept hori-

zontal. This, and the fact that an engine fitted with a conventional carbureter will not continue to run upside down for any great length of time, limits most inverted flights to distances of a few thousand feet.

The Spin.—Although the spin is a maneuver which is easily recognized if once seen, it is difficult to describe. The flight path of the airplane is not straight down, but is helical, that is, in the shape of a corkscrew. The maneuver is further complicated by the fact that the angle of attack of the airplane is very high, so that the nose of the airplane is not by any means pointed along the flight path, and the machine is rolling, pitching, and yawing, all at the same time. The effect of these motions, combined with the peculiar form of the flight path, and the high angle of attack, causes the tail of the airplane as a whole to go around in a circle. Unfortunately the explanation of the spin is complicated and too long to be attempted here. Suffice it to say that the essential characteristic of the spin is the very high angle of attack of the wings to the flight path. This may reach values not only above the stalling angle, but even as high as 60° . The spin can continue only so long as the angle of attack remains above the stalling angle, and it cannot begin until the angle of attack has reached the stalling value. If, therefore, the airplane can be prevented from stalling, it can be prevented also from spinning, and even after it has started spinning it will stop if brought out of the stall. Since the airplane when spinning is descending very steeply, the natural inclination of the untrained pilot in attempting to bring it out is to pull back on the stick to raise the nose. This is exactly the wrong thing to do. The correct action is to push forward on the stick, so as to reduce the angle of attack. Once this has been brought below the stalling angle, the spin stops, and becomes a straight dive, from which recovery is easy.

A spin begun at a low altitude is a highly dangerous maneuver, since recovery is possible only after a considerable loss of height, and a crash from a spin is almost invariably serious because the airplane strikes the ground nearly head-on. It is not surprising, therefore, that statistics show spins to be the cause of a large proportion of the serious airplane accidents. Since most airplanes will spin under certain conditions, pilots must be trained

in spinning so that they may know how to deal with a spin should it occur accidentally. Deliberate spinning for other than training purposes belongs definitely in the class of exhibition stunts and military maneuvers.

Roll.—A roll is merely the result of a rolling motion continued in the same direction long enough for the execution of a complete rotation of 360° about the longitudinal axis. The conclusion of the maneuver finds the airplane in its original attitude. It may be performed simply by applying the ailerons, but more often it is carried out by first increasing the angle of attack and then making the machine execute what is essentially a spin with the axis of the helical flight path horizontal instead of vertical. A combination of roll and loop gives a pilot a means of changing direction very rapidly. He may first execute a half loop, and then when the airplane is upside down follow this with a half roll, thus bringing the machine out right side up, and headed in a direction opposite to that at the beginning of the maneuver. This is the Immelmann turn, made famous during the war by the German pursuit pilot of that name.

The possible maneuvers of an airplane are by no means limited to those which have been described. A properly designed airplane in the hands of a skilful pilot may be made to execute highly spectacular evolutions, and under some circumstances it may be difficult even for the pilot to tell precisely what the airplane is doing. Such "stunts" or acrobatics, however, should be indulged in only by pilots thoroughly trained, and using machines designed for this sort of work. In ordinary commercial flying, other than training, acrobatics have little place, and the pilot's object should be to handle his airplane with the fewest possible sensations to his passengers.

CHAPTER XII

AIRPLANE CONSTRUCTION

The twin essentials in the structure of an airplane are strength and lightness; the first without the second is useless, and the second without the first is dangerous. The structural designer must, therefore, steer a close course between Scylla and Charybdis, and only skilful compromise can lead to success. As if these difficulties were not enough, there are requirements of rigidity and low air resistance to be met, and economy in cost must not be overlooked.

In ordinary engineering structures, such as bridges and buildings, a large factor of safety is customary, and the strength is sufficient to withstand a load much greater than the largest which can ever come on the structure. In the airplane the need of lightness prevents this practice from being followed. The term "factor of safety," often used in connection with airplanes is a misnomer; the correct term is "load factor." A factor of safety is based on maximum possible load, and if a structure has a factor of safety of 4, then the greatest load which can ever come on it is only one-fourth of that required to break it. A load factor, on the other hand, is based on normal load, so that if the structure of an airplane is designed for a load factor of 7, it is just strong enough to carry a load seven times that which comes on it in steady horizontal flight. It has already been pointed out, however, that in aerobatics the loads on various structural members may be much higher than those imposed in uniform level flight. If an airplane designed for a load factor of 7 were pulled out too sharply from a very fast dive, the load on the wings might be more than seven times that in normal flight, and so cause a failure. The airplane pilot must therefore limit his maneuvers to those which do not impose loads beyond the strength of his machine, and the designer must provide sufficient strength for any maneuver which the airplane may legitimately

be called upon to execute. A military pursuit airplane, accordingly, has a load factor of 12, and a slow commercial machine one of 5.

Rigidity in an airplane structure is almost as essential as strength, for excessive deflection or bending under load may lead to a loss of control, with consequences as serious as those of a definite breakage. Cases have actually occurred in which airplane wings have deflected so much that the pilot lost control of the machine and had to jump.

In seeking strength and rigidity, the primary essential of light weight can never be lost sight of, for every pound of increase in the weight of airplane structure means a corresponding decrease in the useful load which the machine can carry and, consequently, a decrease in military effectiveness or in earning power. The least possible air resistance is also of great importance, for high resistance means increased power required, and, unless the power available is increased, an impaired performance.

With the limited margin of safety permitted by weight limitations, it is highly necessary that the load in every member be accurately determined for several attitudes of flight so that there may be no weak links to fail. Such a determination of loads is called a *stress analysis*. The method employed is based entirely upon the principles of physics and mechanics, and is essentially the same as that used in calculating the loads in various parts of a bridge. It is a complicated process, and distinctly a job for the trained engineer.

The history of 25 years of development and refinement in airplane construction is very interesting, and to it a whole book could well be devoted. In this chapter, however, space permits consideration only of types of construction which are now in use. Since different parts of the same airplane may employ different methods of construction, it is most convenient in discussing the subject, to deal with the different parts of the airplane in order, rather than to describe various airplanes completely.

WING CONSTRUCTION

The ordinary airplane wing, as now built in the United States, has a fairly standard arrangement of members and it is most

logical to consider them in the order in which they participate in carrying the air load to the fuselage.

The conventional airplane-wing covering is a *fabric* of long-staple cotton, with about 90 threads per inch in each direction. It is carefully manufactured and all defective pieces are rejected. In other countries, as formerly in the United States, linen is preferred, but here the long-staple cotton fabric is considerably cheaper, a trifle better, and much easier to obtain. The breadths are first stitched together with double locked seams, making a large blanket. This is laid over the wing in such a way that each breadth extends from the trailing edge forward around the leading edge, and back on the other side to the trailing edge, where the two edges of the blanket are sewn together with a stitch like that used on the cover of a baseball. The fabric is attached to the *ribs* also by long stitches of heavy linen thread passing around them and completely through the wing. When the fabric has been stitched in place, the next step is the application of several coats of *dope*, a solution of cellulose acetate or cellulose nitrate. The dope is spread over the fabric with a brush or a compressed air spray, and dries very quickly, leaving a film or glaze. This glaze is comparatively weatherproof and also resists the passage of air through the wings. The dope also has the further effect of shrinking and strengthening the fabric, so that after the application of several coats, it is drawn up tight as a drumhead. Following the first coat of dope, all the stitches are covered with cloth tape, so that finally the entire interior structure of the wings is covered with a relatively airtight and weatherproof envelope. Eyelets are ordinarily inserted in the fabric on the lower surface, near the trailing edge, so that any water which finds its way inside the wing can readily drain out.

Conventional Wooden Framework.—The main structure of a conventional wood-and-fabric wing is shown in Fig. 133. The *ribs*, which are the chief support of the fabric, run from leading edge to trailing edge. In Fig. 134, are shown several typical airplane ribs of different sizes and types. A common material in the construction of wooden ribs is plywood, which is composed usually of three very thin layers of wood glued together to form a single sheet with the grain of the center layer running at right angles to that of the outside layers. The total thickness of a

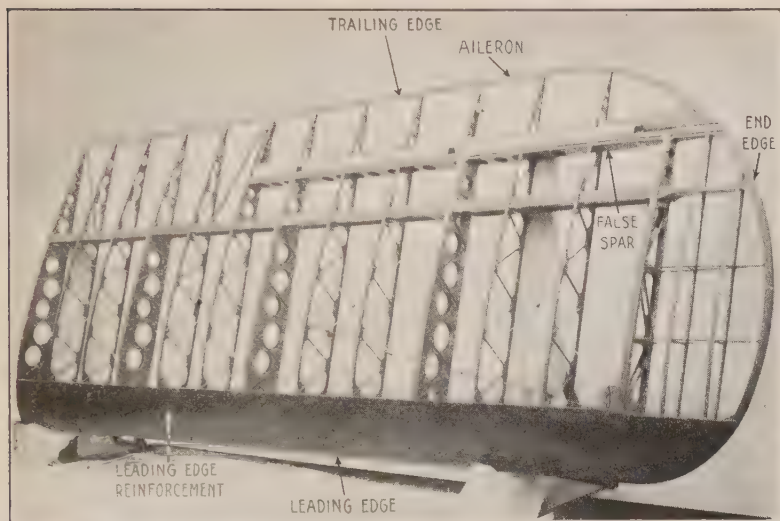


FIG. 133.—Structure of wooden wing for fabric cover. (Courtesy Chance Vought Corp.)

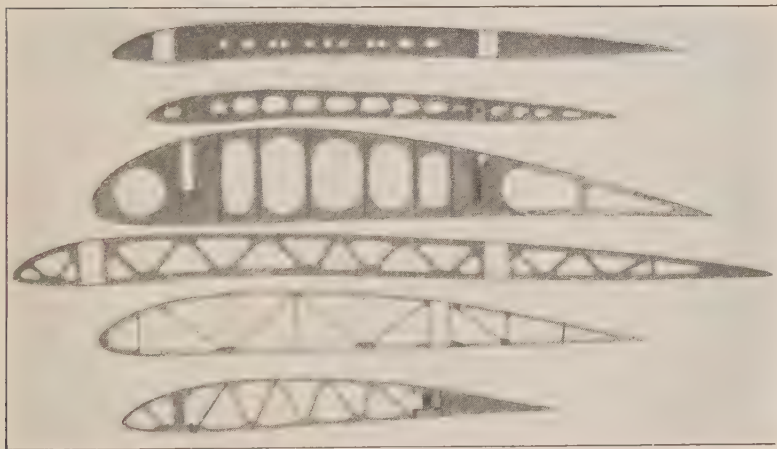


FIG. 134.—Wooden wing ribs. (Courtesy Materiel Division, U. S. Army Air Corps.)

sheet of plywood may be only $\frac{1}{8}$ in. Plywood is stronger and less likely to split than a single sheet of wood of equal thickness. The simplest form of rib consists of a sheet of plywood cut to the correct contour, and provided with additional strips of wood called *capstrips* on the edges to offer more surface against the fabric so that it will not be cut. Large and deep ribs are often made in the form of a truss, like the lower three in Fig. 134. The little diagonal members are spruce, and the chord members, which run the long way of the rib, are of plywood, with capstrips as before. The strength of such a rib is surprising; in tests a rib 9 ft. long, weighing only $15\frac{1}{2}$ oz., has carried a load of 940 lb.

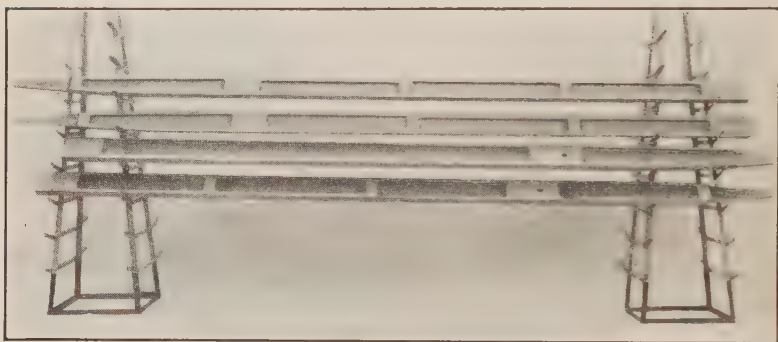


FIG. 135.—Wooden wing spars. (Courtesy Bureau of Aeronautics, U. S. Navy, and Chance Vought Corp.)

The ribs are carried by the *spars*, or *beams*, which are the principal structural members of the wing. Typical wooden spars are shown in Fig. 135. The form of cross-section is ordinarily that of a box, or else is like the letter I. In a box spar, the two edge members, the *flanges*, are usually spruce, while the sides or *webs* are plywood. A spar of I-section is generally cut from a single piece of spruce.

In order that the wing may keep its shape, and carry all the loads which come upon it, some additional structural members are necessary. These are classified in two groups, the *internal bracing*, and the *external bracing*. The former consists of a set of members inside the wing, as shown in Fig. 133, which, with the spars, make a truss much like that of a bridge; the function of this truss is to carry loads which act from front to rear, or

from rear to front, in the plane of the wing. The members perpendicular to the spars, the *struts*, which here take the form of box ribs, are often made of steel or duralumin tubing. The diagonal members are solid steel wires or rods.

External Bracing.—The character of the external bracing varies with the type of airplane. In the pure *cantilever* monoplane there is no external bracing whatever, and the spars themselves are made strong enough to carry the load into the fuselage without external assistance. Since this arrangement



FIG. 136.—External wing bracing of a semi-cantilever monoplane. (Courtesy Fairchild Airplane Manufacturing Corp.)

requires extra weight in the spars, to give them sufficient strength, it is quite common to provide external bracing, as shown in Fig. 136. Two struts on each side run from the bottom of the fuselage to points well out on the wing, and so carry into the fuselage a considerable portion of the lift which would otherwise have to be transmitted by the spars. These external struts are ordinarily made of steel tubing.

In the biplane, as shown in Fig. 137, the system of external bracing is more elaborate; two complete trusses are ordinarily present, one of which connects the upper and lower front spars, and the other the upper and lower rear spars. The vertical members in this truss, the *interplane struts*, are ordinarily made

of steel or duralumin tubing. The diagonal members are generally streamline wires, although in small and light machines round steel cables may be used. The diagonals which run upward and outward are called *lift wires*, because they participate in taking the lift of the wing, and the diagonals which run downward and outward, are called *antilift*, or *landing wires*, because they oppose the lift wires and take the load due to the weight of the wing when the airplane is landing or is at rest on the ground. In addition to these, there is another set which



FIG. 137.—External wing bracing of a biplane. (Courtesy Materiel Division, U. S. Army Air Corps.)

maintain the angle of stagger and are called the *stagger wires*. They run diagonally from front to rear between each pair of interplane struts, as shown in Fig. 137. Proper alignment of the wing structure depends upon a correct adjustment of the length of all these interplane members, and errors may lead to overstrain and serious damage.

Fittings.—The pieces which form the joints between the different structural members are called *fittings*. They are almost always made of metal, whatever the material of the rest of the structure, and vary in form according to the location in which they are used, and the number of members to be con-

nected. Figure 138 shows a typical fitting, a hinge which joins the wing to the fuselage. Figure 139 shows an interplane strut fitting, in place. This not only connects the interplane strut to the spar, but carries also a double lift wire, together with an

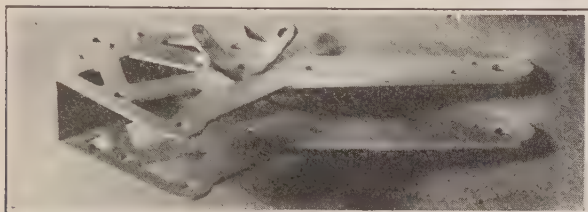


FIG. 138.—Wing hinge fitting. (*Courtesy Bureau of Aeronautics, U. S. Navy.*)

internal drag strut in the form of a box rib, and two internal drag wires. It is obvious that much ingenuity is necessary in a design of fittings in order to make them light, strong, and easy to manufacture. The material ordinarily used for fittings is steel, though some builders now employ duralumin instead.



FIG. 139.—Interplane strut fitting. (*Courtesy Chance Vought Corp.*)

Minor Wing Parts.—In addition to the structural members of the wing, which play an important part in transmitting the air load to the fuselage, there are certain other parts, essential to the maintenance of the correct form of wing, which do not

participate so directly in carrying the load. Among these are the pieces which form the edges of the wing, indicated in Fig. 133 as *leading edge*, *trailing edge*, and *end edge*. The leading edge is often a piece of spruce which runs the entire length of the wing, and is supported by the ribs. Since the air loads on the extreme front of the wing are very high, some additional reinforcement is provided, usually in the form of a continuous strip of plywood between the top of the front spar and the leading edge, as shown in Fig. 133. To give still further strength,

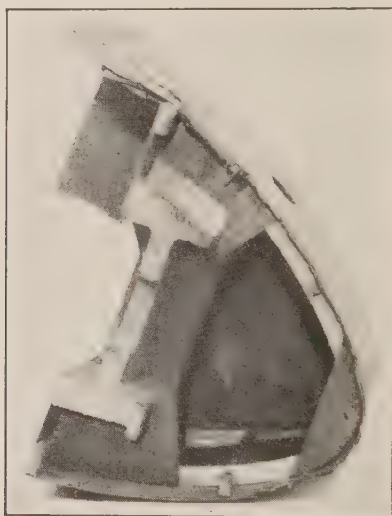


FIG. 140.—Section of front spar and leading edge. (Courtesy Massachusetts Institute of Technology.)

additional small *nose ribs*, which extend only from the front spar to the leading edge, are often provided between the main ribs. In Fig. 140, another type of construction is illustrated, which differs from that just described in that there is no continuous leading edge piece, but instead a plywood reinforcement on both upper and lower wing surfaces. The nose ribs here consist only of cap strips, and the construction is unusual also in that the front spar does not occupy all the available thickness of the wing. The plywood over the leading edge not only gives extra strength, but also maintains the correct wing profile. Without

this reinforcement the sag of the fabric between ribs at the leading edge would affect the form of the wing enough to impair



FIG. 141.—Plywood-covered wing. The covering is in place only on one side.
(Courtesy Atlantic Aircraft Corp.)

its efficiency. As even the main ribs are very light, they must often be supported against tipping over sidewise. This is done

by means of light wood *stringers*, which run parallel to the spars. A gap in the wing structure at the trailing edge near the tip is left for the aileron, and a *false spar* is provided at the front of the gap to carry the aileron hinges.

The conventional type of wing construction just described is relatively simple and comparatively cheap to manufacture, and has good strength for its weight, but there are also other types which are worthy of description.

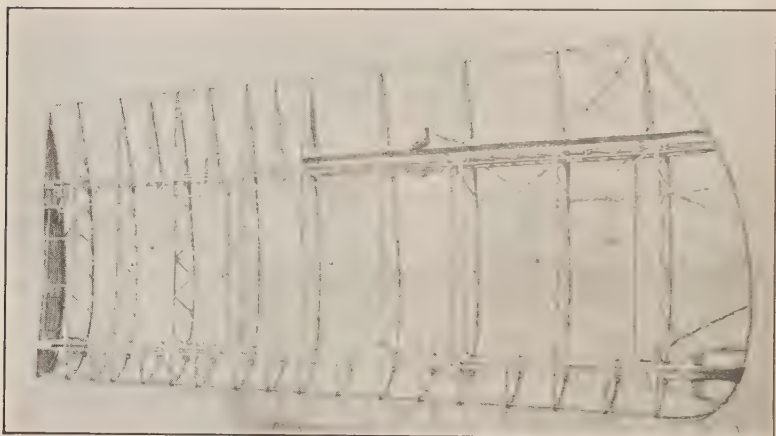


FIG. 142.—Framework of metal wing for fabric covering. (Courtesy Bureau of Aeronautics, U. S. Navy, and Hall-Aluminum Aircraft Corp.)

Plywood Covering.—One common modification is the use of a plywood covering in place of fabric, as in the wing illustrated in Fig. 141. The plywood is composed of three laminations of birch, 0.09 in. thick. Plywood covering offers several advantages to offset the disadvantage of its greater weight. It maintains the correct shape of the wing much better than does fabric, and as it is almost completely weatherproof, it protects the interior structure more effectively. Since wood is obviously stronger than fabric, the ribs can be spaced farther apart than with fabric covering, and much of the internal bracing can be omitted, for the covering itself keeps the spars at their proper distance, takes the air load in the plane of the wings, and prevents the wings from twisting.

Metal Wings.—Metal airplane wings may be divided into two general classes—*fabric covered*, and *metal covered*. Both are widely used.

In the fabric-covered metal wing, the internal arrangement of the parts is much the same as in the wood wing. British aircraft builders have experimented extensively in the construction of wings of this sort with an internal structure of steel, but in other countries the metal usually employed is duralumin, the

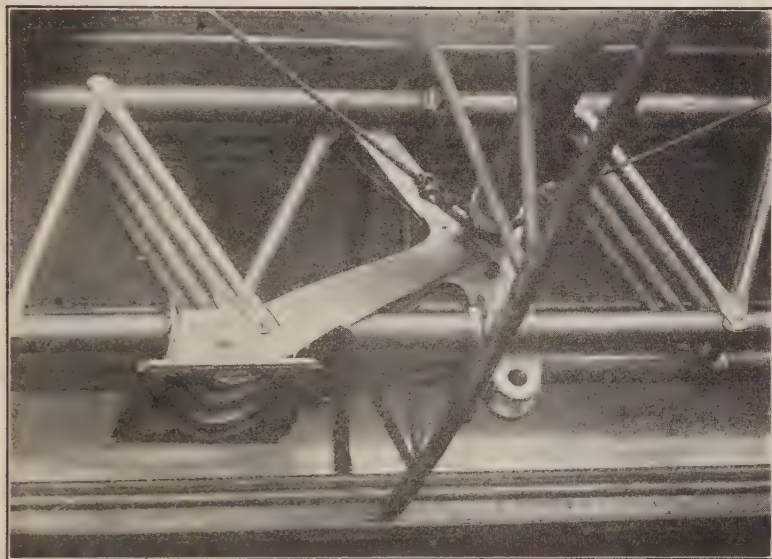


FIG. 143.—Detail of metal-wing structure, showing rib, spar, and internal bracing.
(Courtesy Hall-Aluminum Aircraft Corp.)

light alloy of copper and aluminum already referred to. Figures 142 and 143 show the framework of a wing of this sort. The ribs are composed of light duralumin tubes and rolled sections with riveted joints, and the spars have duralumin tubes for flanges with lighter tubes as diagonals. The edges of the wings are tubes of special shape. The internal drag struts are made of duralumin tubing, but the diagonals are steel rods. The leading edge reinforcement consists of a light sheet of aluminum. Both steel and duralumin are used for fittings. The weight of a wing of this sort is often considerably less than that of a wood

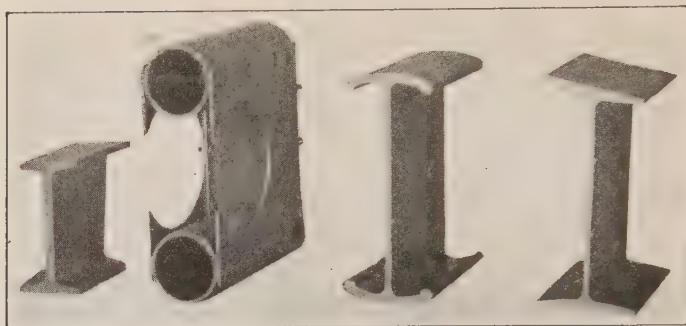


FIG. 144.—Short sections of duralumin wing spars. (*Courtesy Materiel Division, U. S. Army Air Corps.*)

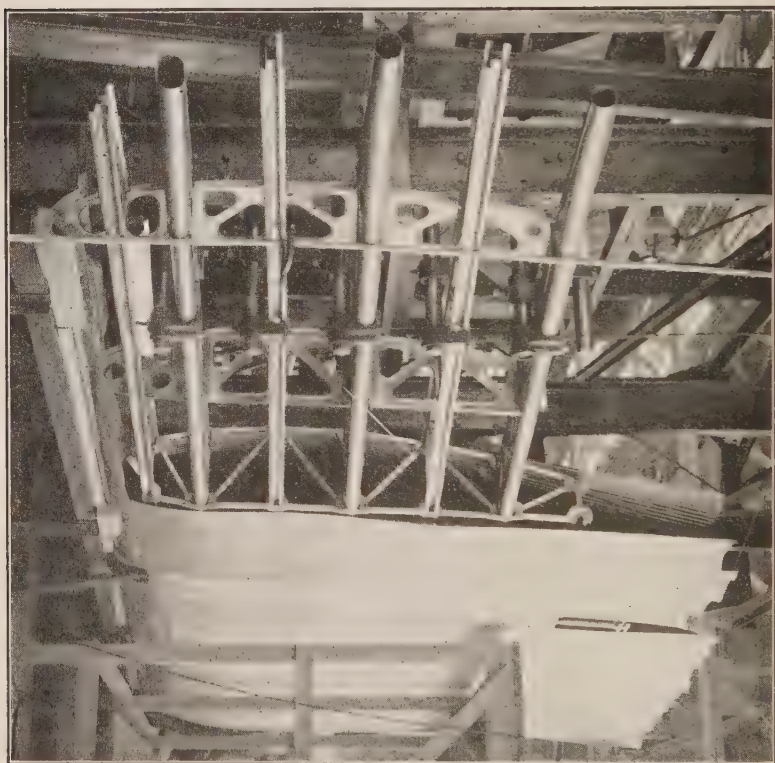


FIG. 145.—Construction of metal wing with sheet duralumin covering. (*Courtesy Ford Motor Co.*)

wing of the same size and strength, but in small quantities the metal wing is still distinctly the more expensive of the two. As airplanes are produced in larger quantities, however, more efficient methods of construction may be expected to give lower costs. Already some manufacturers have made ribs by stamping them almost complete out of single sheets of metal. This process is cheap when the number of identical ribs is large, but otherwise the expense of the tools and dies may be prohibitive. Duralumin wing spars have been made in many designs, several of which are illustrated in Fig. 144.

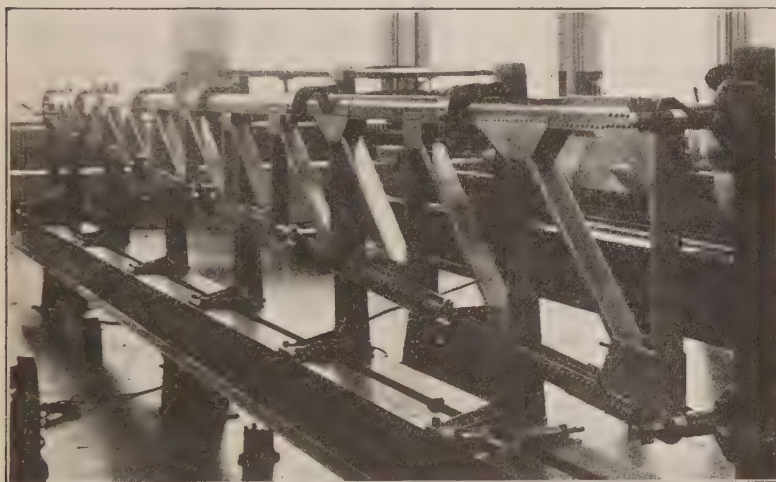


FIG. 146.—Spar for duralumin-covered wing. (Courtesy Ford Motor Co.)

The second class of metal wings employs, instead of fabric, a covering of sheet duralumin, usually about 0.012 in. thick. Figures 145 and 146 show the construction of a wing of this sort. Here three spars are employed instead of the conventional two, with several additional lighter members. The corrugations in the covering give it additional stiffness, and, as they run in the direction of the air flow, add but little resistance. The usual internal drag struts and diagonal wires are omitted, for the loads which they would normally carry are taken care of very well by the metal wing covering. The weight of a wing of this type is likely to be rather more than that of a corresponding wood

wing, or that of a metal wing with fabric cover. The all-metal wing is usually somewhat stronger in proportion to its weight, and is less affected by weather. On the other hand, unless it is large enough so that a man can crawl inside, internal corrosion is hard to detect, though the danger of this may be greatly reduced by proper precautions when the wing is constructed.

FUSELAGE CONSTRUCTION

Types of airplane fuselage construction are very numerous indeed, and space suffices to describe only some of the more common examples. For many years, the standard was the *stick-and-wire* type, in which the *longerons*, the long members running from nose to tail, were made of wood, as were also the

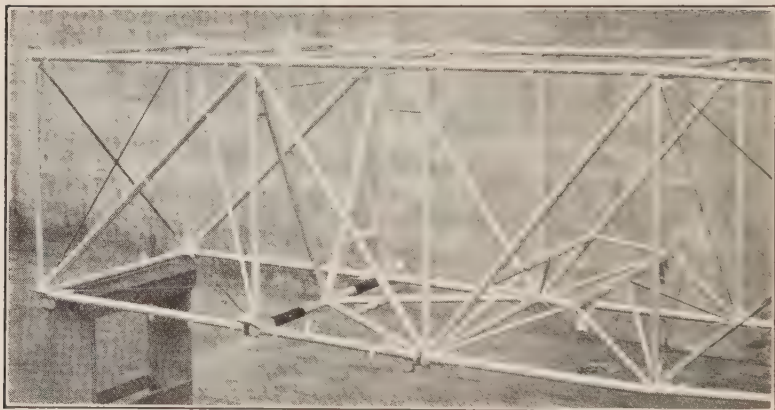


FIG. 147.—Part of a steel-tube fuselage. (Courtesy Wright Aeronautical Corp.)

struts, the vertical and horizontal cross-members between the longerons. The diagonals were of round steel wire, and joints were made with fittings formed by bending from sheet steel. The covering was of fabric. This type of fuselage was relatively easy to build and used common materials, but it did not have as good strength in proportion to its weight as some of the more modern types, was hard to keep in alignment under varying weather conditions, and was likely to splinter badly in a crash. Stick and wire fuselages are now found in the United States only in old airplanes.

Steel-tube Fuselage.—The type of fuselage now constructed in the greatest numbers is that with a framework of steel tubes, such as is shown in Fig. 147. Both longerons and struts are made of round steel tubes of great strength and stiffness in proportion to their weight, and the joints are welded by the oxyacetylene torch. The diagonals may be steel tubes, but

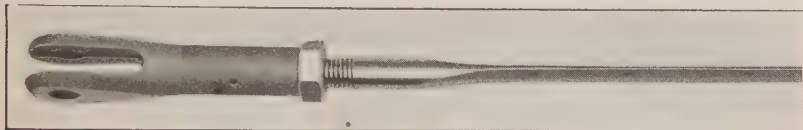


FIG. 148.—Streamline wire and terminal. (Courtesy Stewart Hartshorn Co.)

often are steel wires, or more correctly speaking, steel rods, like those used for internal diagonal wing bracing. These wires may be either round, square, or streamline in cross-section, but in any case the ends are round, and are threaded one right hand and the other left hand. Each end is screwed into a *terminal* or *clevis*, which in turn is attached by a *clevis pin* to a plate at

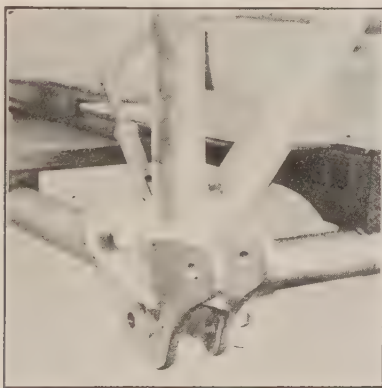


FIG. 149.—Joint in a steel-tube fuselage. (Courtesy Chance Vought Corp.)

the fuselage joint. The end of the wire, the clevis, and the lock nut are shown in Fig. 148, and a complete joint in Fig. 149. Since the ends of the wire have opposite threads, the tension may be adjusted simply by turning it.

Many constructors prefer to build the framework without wires, as shown in Fig. 150, using steel tubes for the diagonals

as well as for the longerons and struts. This type of fuselage is more rigid than that with wire diagonals, but is somewhat more difficult to construct.

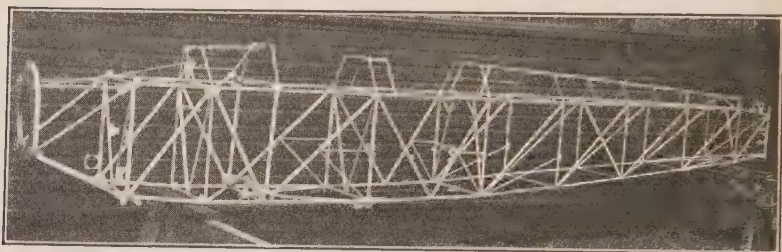


FIG. 150.—Steel-tube fuselage without wires. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)

The construction of a steel-tube fuselage requires good material, skilful workmen, and careful inspection. As the walls of

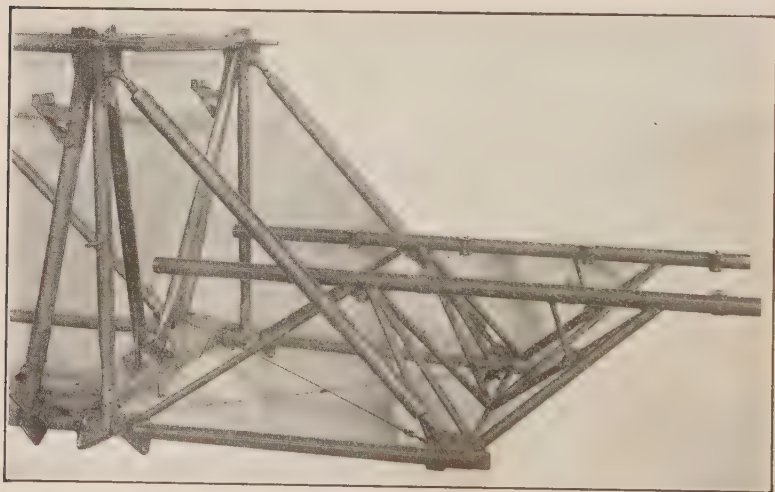


FIG. 151.—Engine mount for V engine. (*Courtesy Curtiss Aeroplane & Motor Co., Inc.*)

the tubes are often less than $\frac{1}{16}$ in. thick, a careless or untrained mechanic may easily overheat and burn the metal in the welding operation. Since a steel tube shortens when welded, each one

must be cut long, so that when the welding operation is complete the length will be correct. The making of this shrinkage allowance requires considerable experience, and mistakes throw the structure out of line. The difficulties just mentioned, while serious for inexperienced personnel, are not a bar to thoroughly satisfactory results in factories which are properly manned, equipped, and supervised.

Minor parts are fastened to the main structure of the fuselage by means of small fittings which are either welded or soldered to

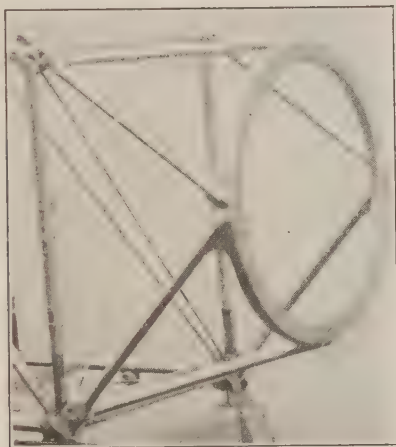


FIG. 152.—Engine mount for radial engine. (Courtesy Bureau of Aeronautics, U. S. Navy, and Chance Vought Corp.)

the steel tubes. Welding is preferred for relatively heavy parts which are attached near the ends of the tubes, while soldering is employed for lighter parts, and particularly for fittings near the middle of a tube, since a welded joint in this location would be an element of weakness.

The *engine mount* is usually of the same construction as the rest of the fuselage, the engine itself being attached to two long *engine bearers* which are provided with fittings having holes for the holding-down bolts. A radial engine is carried on a ring of tubing or of sheet metal. Figure 151 shows a typical engine mount for a V engine; and Fig. 152, one for a radial engine.

In each case the mount can be detached from the rest of the fuselage by the removal of four bolts.

Duralumin Framework.—Fuselages with trussed framework are not all of steel-tube construction, and several manufacturers have built this type with members made of duralumin tubes or of open sections, such as shown in Fig. 153. In trussed fuselages

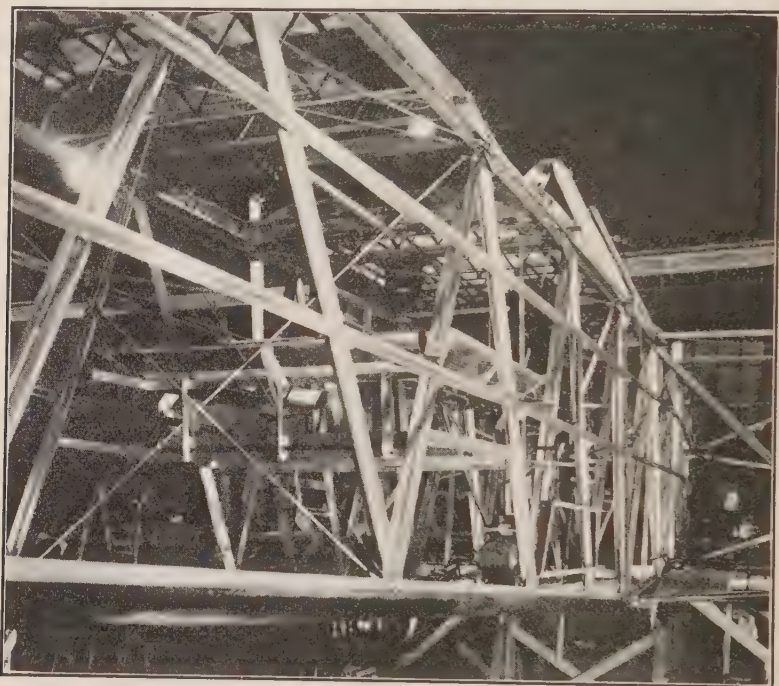


FIG. 153.—Fuselage truss of open-section duralumin members. (Courtesy Sikorsky Manufacturing Corp.)

with duralumin members, however, no method for making reliable welded joints has yet come into commercial use, so that fittings to which the members are held by rivets, as in Fig. 154, must be employed. The duralumin-tube fuselage is likely to be essentially lighter than the corresponding fuselage in steel tubing, but it is ordinarily more expensive to construct.

Covering.—Since the most efficient form of the main fuselage structure is that with a rectangular cross-section, some falsework

is frequently added to improve the external shape. This falsework may be of wood, but the modern tendency is toward

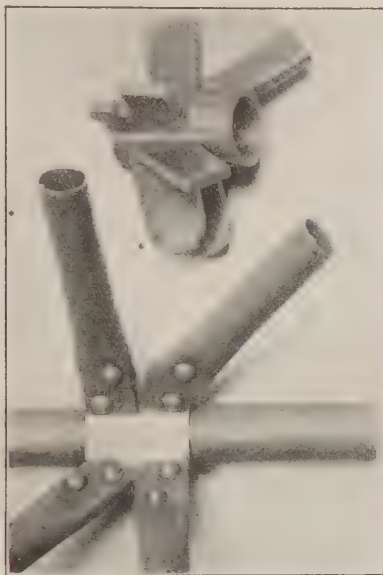


FIG. 154.—Joint in duralumin tube fuselage. (Courtesy Hall-Aluminum Aircraft Corp.)

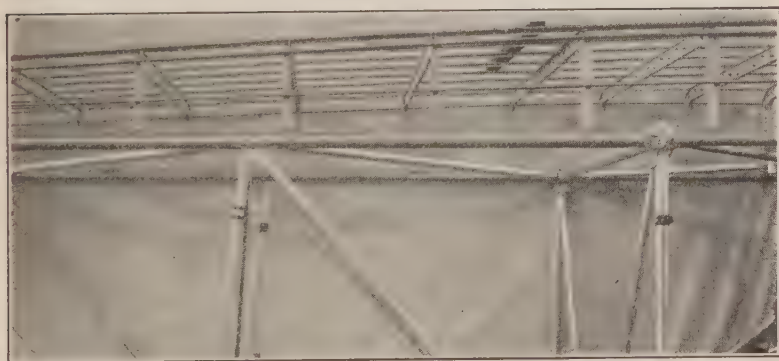


FIG. 155.—Falsework on duralumin tube fuselage. (Courtesy Curtiss Aeroplane & Motor Co., Inc.)

the use of light steel tubing, or duralumin. Figure 155 shows the typical falsework for a duralumin-tube fuselage. The final

covering outside the falsework is of fabric, applied in much the same way as that on the wings, and since the load on this is comparatively low and the consequences of failure not serious, it may be made of material of lower grade than that used for the wings. The fabric is finished like that on the wings, except that fewer coats of dope are used.

The covering or *cowling* over the engine is, ordinarily, sheet aluminum or duralumin, the latter being stronger, but less easy



FIG. 156.—Cowling for water-cooled engine. (Courtesy Wright Aeronautical Corp.)

to manufacture. It is carefully shaped to fit around the engine, and at the same time is given the best possible form to minimize air resistance. Naturally an air-cooled engine cannot be completely enclosed, as the air must flow over the cylinders, but even here the form of cowling is of considerable importance, if the resistance of the airplane is to be kept down. Figure 156 shows a typical cowling for a water-cooled engine; and Fig. 157, one for a radial air-cooled engine. The cowling has to be readily remov-

able so that mechanics may have no difficulty in getting at those parts of the engine which require attention, but at the same time the fastenings must be secure, for the blowing off of a piece of cowling in flight may cause a serious accident.

Metal cowling is ordinarily employed, not only on the engine but also over the fuel tanks, around the cockpits, and at other

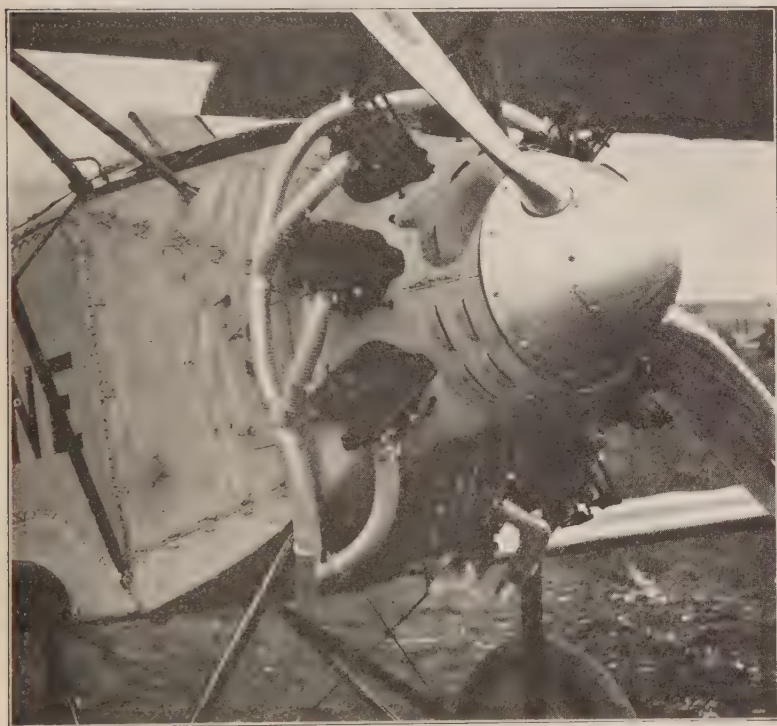


FIG. 157.—Cowling for air-cooled engine. (Courtesy Wright Aeronautical Corp.)

places where something stronger than fabric is needed or where the interior of the fuselage must be frequently reached from the outside.

Fire Wall.—Every fuselage, of whatever type of construction, must have a fire wall between the engine compartment and the rest of the interior. This is usually made of two sheets of

aluminum or duralumin with a layer of sheet asbestos between, and extends completely across the fuselage from top to bottom and from side to side. Naturally, there must be some openings for fuel and oil pipes and for engine-control rods, but these openings are made as small as possible, and are provided with bushings to ensure a snug fit. The whole idea of the fire wall is to delay the passage of any fire which may occur in the engine compartment, so that the pilot may have time to extinguish it, or to land the airplane safely before he is driven away from his controls. The fire wall also prevents smoke or other vapors which may originate in the engine compartment in normal operation from penetrating into the pilot's or passengers' section of the fuselage. If the fuel tank is in the fuselage it is always behind the fire wall, though the oil tank may be in front in the engine compartment, since oil is much less inflammable than gasoline.

All-metal Construction.—Fuselages built entirely of metal are now becoming common, particularly in larger airplanes. Figure 158 shows an airplane with such a fuselage. The interior

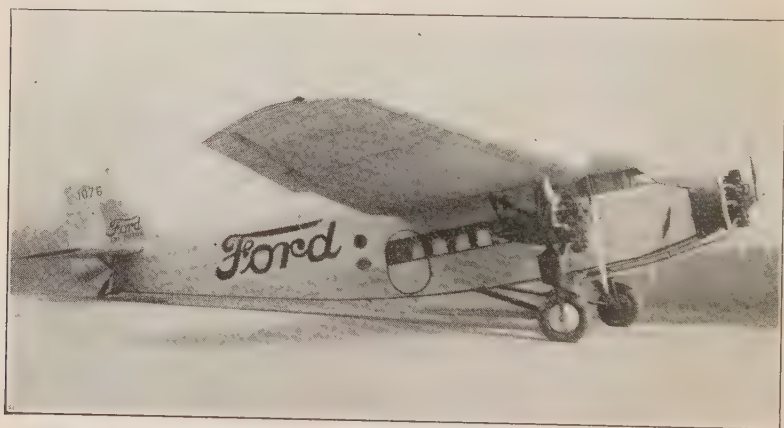


FIG. 158.—Airplane with all-metal fuselage. (Courtesy Ford Motor Co.)

is a framework of duralumin members, and over it is placed a covering of corrugated sheet duralumin. This covering adds considerably to the structural strength, though it is naturally

much heavier than fabric. Toward the rear of the fuselage, the skin or covering is relied upon to carry most of the load, and the internal structure is limited to bulkheads which merely maintain the shape of the cross-section. Figure 159 shows a view of the interior of a fuselage of the type illustrated in Fig.



FIG. 159.—Interior of all-metal fuselage. (Courtesy Ford Motor Co.)

158, and Fig. 160 illustrates the framework before the covering is applied.

Obviously, the all-metal fuselage is much less affected by weather than is the fabric-covered fuselage, but, largely on account of the time required to drive a large number of rivets one by one, it is more expensive to build, and in small sizes is also heavier. In larger airplanes, there is less difference in weight,

and the ability of the all-metal airplane to remain out of doors for long periods without damage may result in a saving in storage expense more than enough to offset its higher first cost.

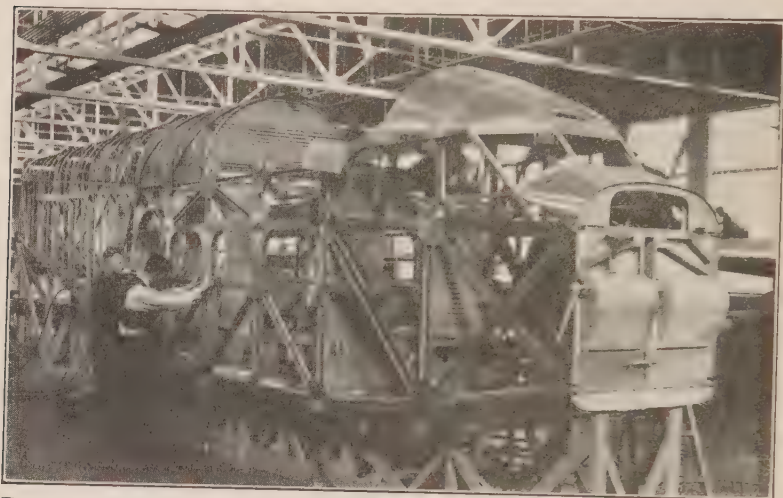


FIG. 160.—Framework of front of all-metal fuselage before covering. (Courtesy Ford Motor Co.)

CONSTRUCTION OF OTHER AIRPLANE PARTS

The wings and the fuselage account for the greater part of the structural weight of the airplane. The types of construction used for the other parts of the airplane depend, to a large extent, on those used for these two main assemblies, since it would not be economical to equip a factory to produce a relatively small part of the machine in a type of construction radically different from that employed for the rest.

Control Surfaces.—Probably the most common type of control surface consists of a light metal framework covered with fabric. Figure 161 shows a photograph of a tail group of this sort. The edges of the surfaces are generally tubes, either round or flattened, and the ribs may be either small tubes or light sheet-metal stampings. From the structural point of view, there is not a great deal to choose between the two types of rib construction, but in large production the stampings are cheaper. All the parts of the framework which come in contact with the fabric are wrapped

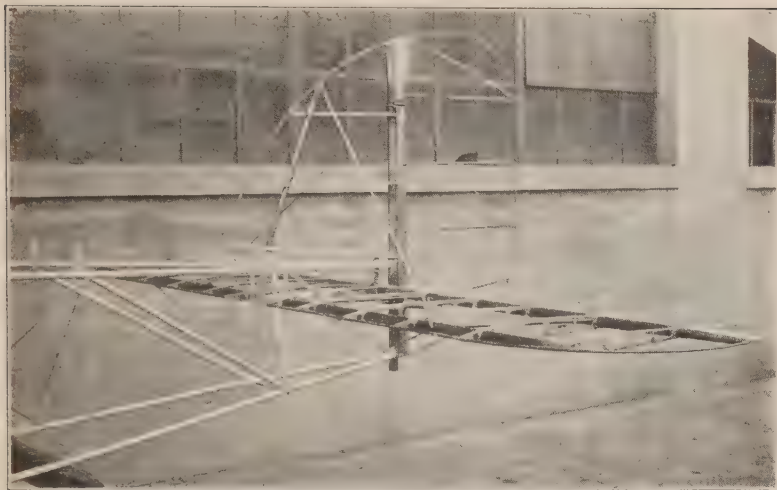


FIG. 161.—Tail group of steel-frame construction. (*Courtesy Wright Aeronautical Corp.*)

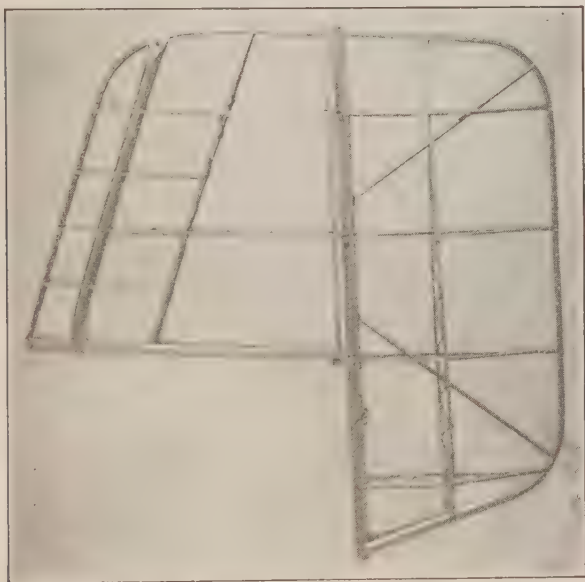


FIG. 162.—Fin and rudder frames of duralumin. (*Courtesy Hall-Aluminum Aircraft Corp.*)

with tape, both to provide a means for attaching the covering to the framework and also to prevent it from being cut by the edges of the metal. It is important that the framework have diagonal bracing members to prevent the structure from being distorted by the pull of the fabric when the dope is applied.

Steel is the most common material for the skeletons of control surfaces, though designers who employ duralumin for the wings



FIG. 163.—Fin of all-duralumin construction. (Courtesy Ford Motor Co.)

generally prefer to use this material also for the control surfaces. Figure 162 illustrates the structure of a fin and rudder made of duralumin. The construction is essentially the same as that of a fabric-covered metal wing. With wood-and-fabric wings the construction of the control surfaces is likely to be of the same type, but it is not uncommon to find control surfaces with steel framework used even where the wings are of wood. Where the wings and fuselage are of all-metal construction, and are

covered with sheet duralumin, the control surfaces are ordinarily built in the same way. Figure 163 shows a fin of this type partly covered. The covering of a small all-metal control surface is ordinarily strong enough to carry most of the load at other points than the horn attachment and hinges, so that little internal framework is needed.

The *horn* or *mast* to which the control cables are attached is invariably made of metal. The main body of the horn is ordinarily formed from a single sheet of steel, with heavier fittings riveted or welded to the ends to provide for attachment of the horn to the control surface, and to carry the cable terminal. If the control surface is made of duralumin, the horn is likewise constructed of this material.

Landing Gear.—As already mentioned, the wheels of an airplane are of the wire-spoke type, unless some special wheel with an internal brake or shock-absorber mechanism is used. The axle is a high-strength alloy-steel tube, and is carefully heat treated. The struts are usually steel tubes, although duralumin tubing is also employed. As the landing gear is the part of an airplane most likely to be damaged, it is desirable to have it readily removable for repair or replacement. The attachment of the struts to the fuselage is therefore made with fittings which can easily be disconnected by taking out the pins.

It is desirable that the landing gear should not be too strong, paradoxical as this may seem. The reason is that if an airplane lands with an excessive rate of descent, some part of it is certain to be broken, and it is much better that part or all of the landing gear should fail than that the fuselage break in two, or some of the landing gear struts penetrate the cabin. Obviously, the landing gear must not be so weak as to fail in an ordinary hard landing, but if in a very heavy landing a considerable part of the kinetic energy of the airplane is absorbed in breaking up the landing gear, the rest of the machine is thus protected.

CORROSION PREVENTION

Hardly anywhere in the airplane outside the engine is metal or wood of very great thickness used. If any corrosion or deterioration occurs, therefore, the effects are likely to be serious, for an amount of rusting which would be trivial on a heavy

steel bridge girder may be distinctly serious in the very light sheet of an airplane spar. While the depth of the corrosion may be the same in each case, the proportion of the total thickness affected is much greater in the thinner material.

For the protection of wood members, dependence is placed chiefly upon varnish, which, if of good quality and carefully applied, forms an almost complete seal against moisture. If the wood dries out too much it will crack, and if it becomes too damp fungus growth or rot may set in, so that the coating of varnish must be kept intact, especially in severe climates. While some of the modern glues are much less affected by water than the older types, the strength even of these is likely to suffer if the wing becomes water logged, or if the airplane is kept in a very warm and damp atmosphere. Deterioration of glued joints is one of the greatest sources of danger in old wooden airplanes. The light nails which are used in these joints merely hold the parts together while the glue is setting, and contribute little or nothing to the strength of the joint afterward.

The protection of metal parts is again a problem of excluding moisture, since it is only in the presence of moisture that metal corrodes. Small parts, like fittings, are readily protected by plating, generally with zinc or cadmium, followed by a coat of enamel. Since plated parts cannot be welded, and a steel-tube fuselage is much too large to go into any plating bath, a structure of this sort can be protected only with varnish or enamel applied after the surfaces have been carefully cleaned.

For preventing corrosion inside steel tubes, the general procedure is first to clean them out as well as possible with a wire brush, and then to fill them with a heavy, hot oil. This oil is allowed to stand for some time, and is then drained out through small holes which are afterwards closed with solder. The sealing of the tubes is effective in itself against corrosion, for it keeps out the fresh supply of oxygen necessary for oxidation.

The liability of duralumin to corrosion is greatly reduced by proper heat treatment in fabrication, but under certain unfavorable conditions this material may be badly affected. Salt water or damp salt air is sometimes dangerous, though its effect is much worse upon commercial aluminum than upon duralumin. A covering of heavy grease is probably the simplest method of protecting duralumin against corrosion, and it is quite effective

so long as the coating lasts. It must be renewed occasionally, and there may be some objection to using it on account of the danger of soiling passengers' clothing. Ordinary spar varnish is widely employed as a protective coating on duralumin. If the surface of the metal is first carefully cleaned and if all traces of grease are removed, the coating adheres well, and so long as it remains intact the metal is protected against corrosion. A process which has come into extensive use abroad, though not yet to a very great extent in the United States, is the *anodic* treatment. This is an electrolytic process carried on in a bath of chromic acid, and results in so changing the chemical characteristics of the surface of the metal as to render it immune to corrosion. The effect of the treatment penetrates to an appreciable depth, so that a slight scratch on the surface is not likely to have a serious effect. Like plating, this treatment can be applied only to pieces of moderate size. Another method just coming into use for protecting sheet duralumin against corrosion consists in applying to it, during rolling, a thin coating of aluminum of a high degree of purity. Since pure aluminum is highly resistant to corrosion, this *Alclad* process appears likely to be of great value.

Fabric requires protection against moisture, and both fabric and dope suffer from the chemical action of light rays. For this reason, a coat of opaque enamel is often applied over the dope, but in recent years it has become more common to use one or two coats of a pigmented dope, that is, one which carries coloring matter in suspension. When the solvent has evaporated, the pigment is left adhering to the surface, and thus the dope provides its own protection against light, as well as that necessary for the fabric under it. Often a coat of clear varnish is used over the last coat of dope to give additional watertightness and protection against spilled oil or gasoline.

Some attempts have been made to render fabrics fireproof, or at any rate slow burning, by the application of some chemical, such as ammonium phosphate, before doping. It has been found, however, that this prevents the fabric from taking the dope as well as it would otherwise, and its use has been largely discontinued. As a matter of fact, the only serious fire risk on an airplane arises from the fuel, and no part of the machine is likely to burn unless the fire is supported by the combustion of gasoline.

CHAPTER XIII

THE SEAPLANE AND THE AMPHIBIAN

Where smooth water is more readily available than level ground, a *seaplane*, able to land upon and take off from the water, has obvious advantages over an ordinary *landplane*, and so serves a definite purpose, even though its field of usefulness is narrower than that of the more common type of airplane which operates

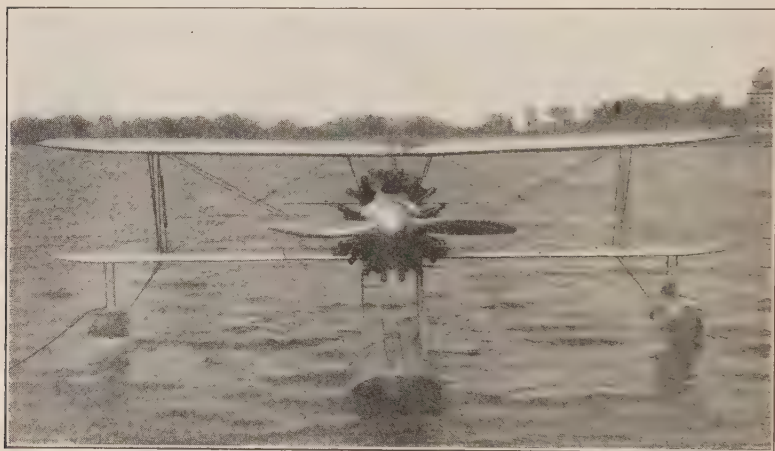


FIG. 164.—The Wright Apache equipped with one main float and two wing-tip floats. (Courtesy Bureau of Aeronautics, U. S. Navy, and Wright Aeronautical Corp.)

only from the ground. The term *seaplane* is a general one applied to all airplanes designed to float on the water and is synonymous with *hydroairplane*, a word too clumsy ever to have come into common use. A *hydroplane*, however, is a boat which skims on the surface of the water and not an airplane at all.

The *amphibian* airplane, or, more often, simply *amphibian*, is an airplane capable of landing upon and taking off from land or water without any change in its parts other than adjustments which the pilot can make in flight.

Seaplane Types and Arrangements.—Seaplanes are divided into two principal groups—*float seaplanes* and *flying boats*. The float seaplane is essentially a landplane with floats substituted for the wheels, as shown in Fig. 164. Either one or two main floats may be used. The landing gear with a single, central float is probably the more common arrangement, even though it involves the use of wing-tip floats to keep the machine from rolling over when it is at rest on the water. These add weight and resistance, and may give trouble in a rough sea. The

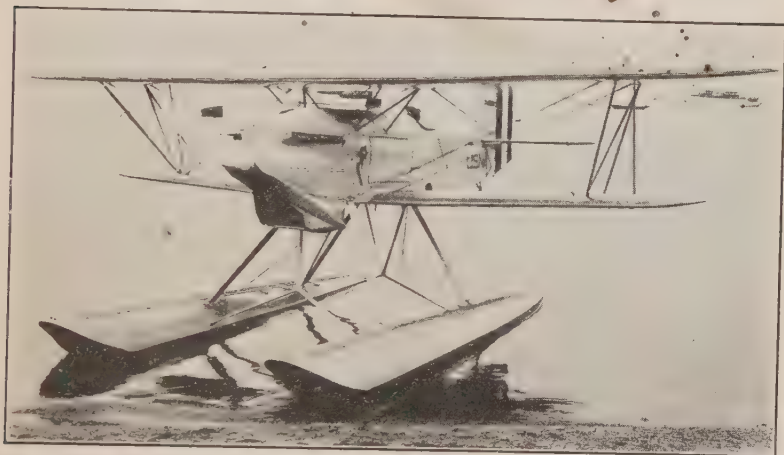


FIG. 165.—The Curtiss *Hawk* as a twin float seaplane. (Courtesy Bureau of Aeronautics, U. S. Navy.)

twin-float seaplane illustrated in Fig. 165 dispenses with wing-tip floats, but must have a rather more complicated system of bracing between the floats and the fuselage. This additional bracing leads to an increase in resistance and weight, particularly as the weight of two floats each large enough to support half the airplane, is more than that of a single float of the same total displacement. Each float arrangement, nevertheless, has special advantages for particular purposes, and each is widely used.

The Flying Boat.—The flying boat differs from the float seaplane in that the hull which provides the necessary flotation is also a container for part or all of the useful load, and is largely or wholly below the wings, even in a biplane. The engine, therefore, usually cannot be carried in the hull, but must be

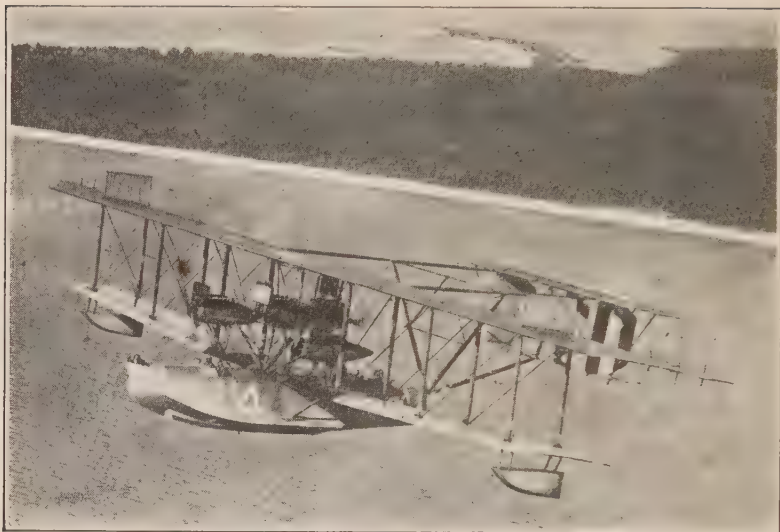


FIG. 166.—The NC-4 flying boat, the first airplane to cross the Atlantic. (Courtesy Bureau of Aeronautics, U. S. Navy.)



FIG. 167.—Tail surfaces carried on outriggers. (Courtesy Bureau of Aeronautics, U. S. Navy.)

mounted higher up, so that the propeller will clear the water. The engine, or engines, are often enclosed in small streamlined bodies called *nacelles*, which may be placed on the wing in a monoplane, or between the wings in a biplane. Figure 166 shows a biplane flying boat in which the four engines are carried in three nacelles between the wings. The flying boat, like the single-float seaplane, requires wing-tip floats, unless, like the Dornier types, it has watertight stub-wings extending out from the bottom of the hull. The tail surfaces of the flying boat are usually carried on the stern of the hull, but sometimes, as in Fig. 167, they are supported on *outriggers*, or *booms*. This arrangement permits a shorter hull, but involves more complication in the tail-surface bracing.

Seaplane Construction.—The fuselage of a float seaplane and the wings and control surfaces of any seaplane do not differ essentially in construction from the corresponding parts as employed in the landplane. The float and hull, however, do not greatly resemble, either in form or in construction, any parts used in landplanes.

Both the seaplane float and the flying boat hull must be adapted to the needs of the airplane under three different conditions: (1) rest, or slow motion through the water; (2) rapid motion on the surface of the water; and (3) flight through the air. The first two conditions obviously demand that at least part of the structure be watertight, and the third that the form be one of low air resistance. The second condition calls for a small water resistance. The usual requirements of high strength, rigidity, and light weight obviously hold for floats and hulls just as for other airplane parts.

To support the airplane with a proper margin of safety when it is at rest on the water the float or *pontoon* must be large enough so that if it were wholly submerged it would displace a weight of water considerably greater than the total weight of the machine. Under ordinary conditions the float rides partly out of water, with only about half its volume submerged. The hull of a flying boat is usually much larger than this in proportion to the weight to be supported, and floats at rest with only about one fourth of its volume under water. The higher freeboard of the flying boat hull is needed, however, so that water may not wash

into the cockpit or into other openings in the deck. Waves breaking over a completely watertight seaplane float do no harm whatever.

The float or hull must be long enough to prevent the airplane from nosing over forward or dipping its tail into the water. In a float, this necessity of keeping the tail out of the water involves greater length and a larger cross-section at the stern than would be adopted if the form were determined solely with a view to minimum air resistance.

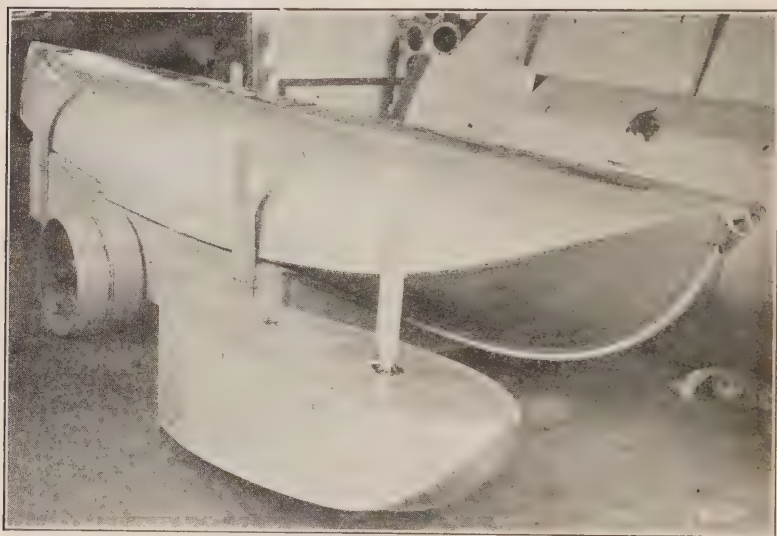


FIG. 168.—Main float and wing float. (*Courtesy Wright Aeronautical Corp.*)

The shape of the float or hull is of great importance, since it is only when this is correct that the seaplane is able to get off the water. Figure 168 illustrates a main float of a form widely used in the United States. In side view the top line of the deck is practically horizontal from stem to stern. The bottom line of the keel curves downward, at first sharply, and then more gently until near the middle it is substantially parallel to the line of the deck. About six-tenths of the distance back from the bow there is an abrupt break, or *step* in the bottom, behind which the keel slopes upward and backward to the stern. In cross-section the deck or upper surface of the float is an arc of

a circle, and the bottom has the form of a V with the keel at the vertex.

The bottom of a flying-boat hull usually has a form much like that of a seaplane float, but the sides rise nearly straight and the deck is relatively flat. In the deck are openings for the cockpits, and, if necessary, for the installation and removal of the useful load.

Float and Hull Construction.—Until recent years, wood was almost the only material used for hulls and floats. The first step in the construction of a wooden float is the building of an

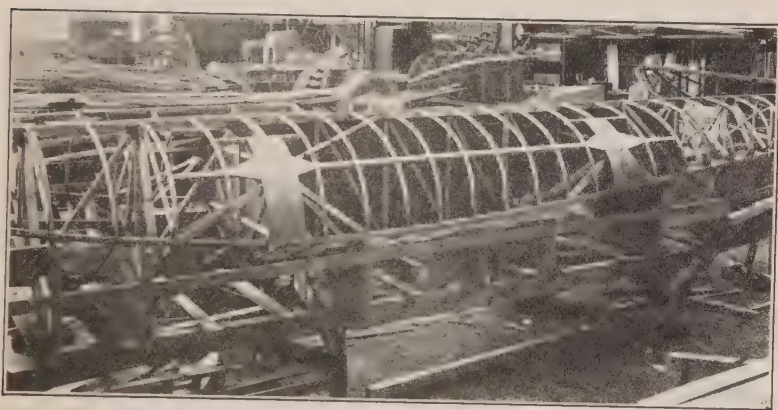


Fig. 169.—Frame of wooden float. (Courtesy Bureau of Aeronautics, U. S. Navy.)

internal framework, such as is shown in Fig. 169. This ordinarily consists of a central truss running longitudinally, with the keel at the bottom, and several cross-bulkheads, together with numerous cross-frames and ribs to stiffen the sides and to maintain the shape of the deck. Since the loads on the bottom of the float in landing are large, additional longitudinal members called *keelsons* are provided to stiffen it. These are shown in Fig. 170, together with the *chines*, which make the joint between bottom and sides. Chines, keelsons, and keel are all bent to the form of the float before being built into the framework. Most of the cross-frames are open trusses, but others are closed by partitions of light wood, dividing the interior of the float into several watertight compartments.

When the interior framework is complete it is covered with spruce planking, the individual planks consisting of strips of wood about 2 in. wide and $\frac{1}{16}$ in. thick. The inner layer is fastened to the framework with small brass screws, and to ensure watertightness each screw is coated with marine glue or cement before being driven. Wherever the covering comes in contact with a bulkhead, the joint is made watertight with marine glue. After the first layer of planking has been applied,

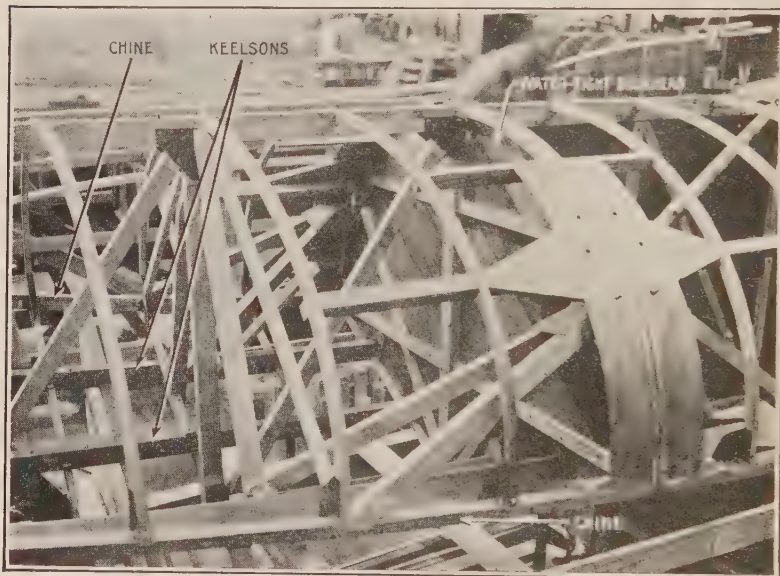


FIG. 170.—Details of frame of wooden float. (Courtesy Bureau of Aeronautics, U. S. Navy.)

it is completely covered with marine glue, and over this glue a sheet of canvas is applied with a hot iron, so that the glue strikes through it. Over this is a second layer of planking, fastened by screws which penetrate into the framework. The planks are generally laid on diagonally, those of the second layer approximately at right angles to those of the first. This arrangement of planking, together with the canvas between the two layers prevents a long crack from developing if the float should be punctured.

After the covering is complete, a longitudinal strip of wood, called the *false keel* is screwed on the outside. This is generally made of ash to resist splintering, and to carry the weight of the machine when it is resting on the beach or on a handling truck.

To empty water from the float when it is hauled out, each compartment has a drain plug which can be taken out either from the outside or through a handhole in the top of the compartment. The handhole has a removable watertight cover, and offers a means of inspecting the inside of the float.

The construction of a wooden flying-boat hull is much like that of a wooden float, but since the flying-boat hull is generally larger than the float, additional framing is often needed. As the flying-boat hull has a great deal of reserve buoyancy and so ordinarily rides high in the water, the bulkheads are sometimes watertight only for part of the distance up from the keel. In other cases, the bulkheads extend all the way from keel to deck, but have openings in them so that the crew may have access to all parts of the hull. These doors, however, are generally in the upper part of the bulkhead, so that no water can run through unless it rises to a considerable height in the flooded compartment.

Wooden floats and hulls are strong, rigid, and relatively simple and cheap to build. Though light when new, the wooden structure soaks up water and increases considerably in weight if it is moored out very much. The free water which inevitably leaks in can, of course, be removed by draining, but the soakage can be eliminated only by giving the float a long period in which to dry out. The wooden float is relatively easy to damage, even in very minor accidents, and since many parts are alternately wet and dry it may deteriorate more rapidly in service than other airplane parts.

The disadvantages of wood as a material for floats and hulls have led in recent years to the extensive use of metal in float construction, in spite of the fact that such a change involves a considerable increase in cost. Metal floats and hulls are almost invariably made of duralumin. The internal framework, as shown in Fig. 171, largely duplicates that of a wooden float, but the individual members are rolled from sheet metal, and in cross-section are usually of U, channel, or angle form. The

joints all have to be made with rivets, since, as previously mentioned, duralumin cannot readily be welded or soldered. To make a watertight joint, a strip of canvas soaked in a paint made largely of asphalt is laid in between the two pieces of metal before the rivets are driven. The asphaltum paint, in addition to making the joint watertight, is very effective in preventing corrosion. The covering of the float is of duralumin sheet, of the same sort as used for wing and fuselage covering, but thicker, and not corrugated. Watertight compartments, drain plugs, and handholes are provided as in wooden floats. Frequently, the whole inside of a float is coated with asphaltum

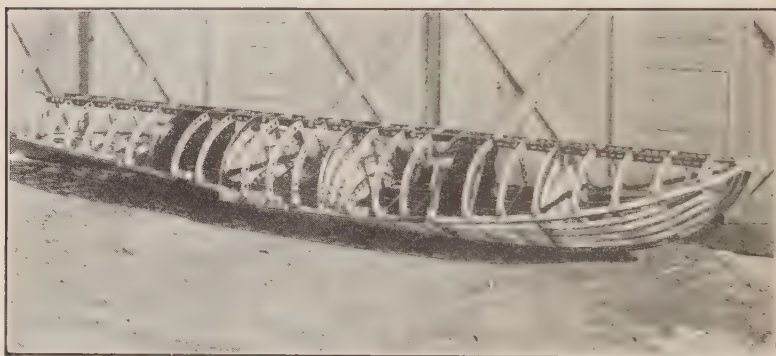


FIG. 171.—Frame of all-metal float. (Courtesy Wright Aeronautical Corp.)

paint, for it is here that the danger of corrosion is greatest. The outside is protected by a coat of spar varnish or grease.

Because of the fear of an extreme tendency to corrosion, particularly in salt water, the metal float was regarded with suspicion for a considerable time after its first appearance. Extensive experience has shown, however, that this danger is much less than had been supposed, and many duralumin floats have been in service for several years without any difficulties due to corrosion.

All-metal flying-boat hulls resemble wooden hulls in shape, and all-metal fuselages in construction, except for the matter of watertight joints. As in the metal float, the bottom plating has to be comparatively heavy, sometimes as much as $\frac{3}{16}$ in. thick, to

withstand the high loads in landing and take-off. It must also be reenforced by internal braces at frequent intervals. Figure 172 shows the construction of an all-metal hull for a modern flying boat.

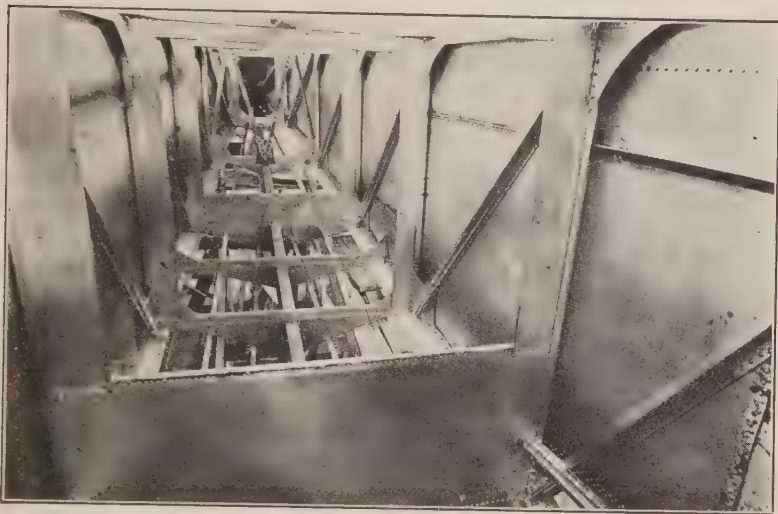


FIG. 172. —Interior of all-metal hull. (Courtesy Bureau of Aeronautics, U. S. Navy.)

Seaplane Flight Characteristics.—Every flight of a seaplane ordinarily begins with the machine at rest in the water. The propeller thrust which is set up as soon as the engine starts gives the machine a forward motion which results in impact of the water against the sloping bottom of the hull. This impact produces lift in the same way as does the impact of air against an airfoil, and the resulting upward force raises the float partly out of the water, with a consequent decrease in resistance. As the resistance decreases, the speed increases, and the lift of the water on the hull increases still more. Meanwhile, the wings begin to lift, also, and so take some of the weight off the floats. The float rises still more in the water until finally it is *planing* along the surface, with only its bottom in contact with the water, and the sides completely out. Once the float is planing well, its resistance decreases considerably and the speed rapidly rises, so that pres-

ently the wings are able to carry the full load of the airplane, and the machine lifts off.

The step in the bottom line of the float makes the water break away at this point without following along all the way to the stern. Were it not for the step, the water would produce a downward suction on the rear portion of the float bottom, and so prevent it from rising from the water. When the float is planing "on the step," most of it is out of the solid water, as shown in Fig. 173.



FIG. 173.—Seaplane "on the step." (*Courtesy Bureau of Aeronautics, U. S. Navy.*)

The behavior of a float seaplane in the air is not essentially different from that of a landplane, except that the greater weight and resistance of the seaplane float combine to reduce the performance below that of the corresponding airplane with wheels only.

The flight characteristics of the flying boat are likely to differ from those of a float seaplane or landplane not only in performance but also in stability. Since in the flying boat the propeller has to be set very high in relation to the rest of the machine, the propeller thrust tends to make the machine nose down. This tendency has to be counteracted by setting the

horizontal tail surface at a considerable negative angle, so that there is a large download on the tail surface to offset the diving tendency of the propeller thrust. Under these conditions, the balance of the machine is satisfactory as long as the engine is running, but if it stops, the diving effect due to the propeller thrust disappears completely while the stalling tendency from the horizontal tail surfaces, though diminished, is still considerable. A sudden engine failure is therefore likely to lead to a stall unless the pilot is alert to prevent it by prompt use of the elevators. This difficulty is probably more serious, however, in the older flying boats than in more modern machines, where both wings and propeller are lower in relation to the hull.

Landing a seaplane or flying boat under favorable conditions is relatively simple, as the pilot merely "levels off" just over the water and allows the machine to settle in slowly, with the engine idling. The float then planes on the surface of the water, and as it loses speed gradually settles deeper until finally the machine comes to a stop. Should the machine descend too rapidly, however, or strike a wave, it may bounce off the water to a considerable height. Such a maneuver is always annoying to passengers, and may even be dangerous, particularly if the airplane has lost flying speed, and stalls after bouncing off. A condition of extremely smooth and "glassy" water often offers peculiar difficulties in landing, because of the deceptive impression which it gives the pilot as to his height above it. He may, therefore, level off too soon, with the result that the airplane loses flying speed before it touches the water and drops in with a severe shock; or he may fail to level off soon enough, and so drive the machine into the water with considerable force. In really rough water, the difficulty in landing is that the machine may strike the crest of one wave, bound off, and bury itself in the side of the next one, and so be swamped or badly damaged.

Seaplane Uses and Advantages.—In spite of the fact that its performance is not so good as that of a corresponding landplane, the seaplane has a distinct field of usefulness. For flights out of gliding distance of land, a seaplane is, obviously, a far safer craft than a landplane, for in good weather it can remain afloat indefinitely if forced down, while a landplane usually sinks in a short time.

In general, it is less dangerous to fly a seaplane over land than it is to fly a landplane over water. For operations over very rough or heavily wooded country where lakes are numerous, the seaplane may even be definitely the safer airplane. In flying over unmarked territory under conditions of poor visibility, it is frequently possible for a pilot to locate lakes and rivers much more easily than landing fields, so that his chances of a successful forced landing are better in a seaplane than in a landplane. A flying boat can even upon occasion make a fair landing upon dry land simply by sliding along the surface of the ground until it stops. Naturally, there may be minor damage in this operation, but a skilful pilot often can avoid anything more serious. A float seaplane, however, is very likely to nose over in such an attempt.

The greater parasite resistance of the seaplane as compared with the land machine may be overcome, to some extent, by a reduction in wing area. A higher minimum speed for a seaplane than for the corresponding land machine is often entirely justifiable, because the seaplane usually has much the larger space in which to land and take off, so that an increased length of run is not a serious disadvantage.

The *convertible airplane* is a conventional machine so arranged that a float-type landing gear may readily be substituted for the landing gear with wheels, should occasion arise. Such an airplane is shown with floats in Fig. 164 (p. 232) and with wheels in Fig. 2 (p. 3).

Amphibians.—An amphibian is essentially a seaplane, usually a flying boat, with wheels which can be lowered into a position below the bottom of the hull when the pilot wishes to alight on land. Figure 174 shows two views of such an airplane, one with the wheels down, and the other with them up. In this machine, the landing gear is operated by a hand crank, with which the wheels can be raised or lowered in 15 seconds.

The performance of an amphibian is not only inferior to that of the corresponding landplane, but also frequently below that of the equivalent seaplane, since the wheel landing gear and its operating mechanism involve additional weight and resistance. The great advantages of this type of airplane are, however, quite evident and make it peculiarly well suited for certain



(a)



(b)

FIG. 174.—The Loening Amphibian: (a) wheels down; (b) wheels retracted.
(Courtesy Loening Aeronautical Engineering Corp.)

types of service, particularly for flights over alternate wide stretches of land and water. An amphibian is especially adapted also for flying along the coast, since when long stretches of smooth beach are available it can alight on land, and, when this is not possible, it can alight in the water just off the beach, and then lower its wheels and taxi ashore under its own power.

CHAPTER XIV

THE COMMERCIAL AIRPLANE

A pioneer in air transport has defined a commercial airplane as one which* can support itself in the air financially. This definition is fundamental, for unless an airplane can earn enough to make its operation profitable it ceases to be a commercial airplane, and becomes simply a device for private amusement. The commercial airplane, therefore, must be so designed and constructed that it can render a desirable service at a price which people are willing to pay.

Uses of the Commercial Airplane.—While *air transport* is the most conspicuous activity of the commercial airplane, it probably is not yet the most extensive, nor the source of the greatest income. The term *aerial service* has been devised to cover those uses of the commercial airplane which are not clearly air transport, and under this designation so many different activities are included that only a few of them can be mentioned here.

The training of pilots is one of the most important phases of aerial service, and many small commercial airplanes are designed largely for this work. Another extensive field of commercial operation is "joy riding," that is, carrying passengers on short flights which end at the starting point. Where interest in aviation is keen and the desire to fly is widespread, joy riding has proved highly profitable, for it gives vent to the aeronautical ambitions of large numbers of people at moderate cost.

Another very important branch of aerial service work is aerial photography. In the past few years, the use of photographs taken from the air has become very extensive, particularly by newspapers desirous of obtaining pictures of the scenes of disasters and other news events that cannot be reached quickly in any other way than by air. Airplanes are widely used also in taking systematic series of pictures of whole areas of ground. From these photographs maps are made, and often the cost of

a map made in this way is lower than that by any other method which would give equally complete, reliable, and detailed results.

Commercial airplanes have been called on for service in many emergencies, to carry aid into regions which have been afflicted with some disaster, and to obtain the information needed for organizing relief. The peculiar advantage of the airplane for this work lies in the fact that no roadway need be prepared for it, so that it can arrive promptly at the scene of the emergency.

Air Transport.—The transportation of passengers, mail, and freight by air is rapidly becoming a well-established industry. As compared with other means of transportation, the airplane has two important advantages—its higher speed, and its ability to fly very nearly in a straight line without much regard to the character of the ground beneath. Where ordinary means of transport are highly developed, the advantage of the airplane lies primarily in its speed, and this must be high enough to offset the time lost in terminal delays if air transport is to be of any real value. In newly settled regions, where the older forms of transport are but little developed, it is the ability of the airplane to disregard obstacles, and to carry passengers in comfort which makes it so useful. Here the speed of the airplane is less important, for its competitors are hopelessly outdistanced from the start.

Characteristics of the Commercial Airplane.—In the eyes of the prospective user of commercial air transport, safety and reliability are essential, and no airplane which does not possess these two characteristics to a high degree can be seriously considered. With the design in the hands of competent engineers, safety against actual breakage of any part of the airplane is relatively easy to secure, and accidents due to this cause are rare. Neither is it difficult to give the airplane flying characteristics such that under ordinary conditions a pilot of average ability can operate it safely. In controllability under unusual and severe conditions, however, there is still something to be desired, though it can safely be said that the needed improvements are fairly definitely in sight, and that their adoption will not be long delayed.

Reliability of operation, that is, freedom from interruption of flights arising from mechanical difficulties in the machine

itself, has been attained to a surprising degree and is constantly improving. To ensure this reliability, however, it is essential that every part of the airplane and power plant be maintained in the best of condition. This maintenance involves frequent and painstaking inspection by the ground personnel, and the immediate correction of any defect, however slight, which the inspection may reveal. It is a commonplace that those organizations which enjoy the greatest freedom from mechanical troubles in the air are those which have given the most careful attention to their methods of airplane and engine maintenance.

It should be realized that mere freedom from mechanical difficulties is not sufficient, in the present state of the art, to ensure entire reliability of operation. Difficulties of navigation and those caused by weather conditions are largely beyond the power of the aeronautical engineer and the aircraft builder to correct. The problem of long-distance airplane navigation under conditions of poor visibility is a formidable one, but it appears to be well on its way to a practical solution. There still remain, however, two very serious problems: landing an airplane in a fog, and preventing the accumulation of ice in large quantities on the airplane under certain conditions of temperature and humidity. Satisfactory solutions of both of these problems are to be expected eventually, but until they are forthcoming it can hardly be said that the airplane is a reliable means of transport under all weather conditions.

Since every airplane will finally wear out after long service, an operating company must set aside funds from day to day against the time when its airplanes must be replaced by new ones. This expense of replacement, or *depreciation*, has proved to be one of the largest items in the cost of airplane operation, and emphasizes the importance of low first cost in commercial airplanes. Much remains to be done in reducing this cost, for until quite recently the number of airplanes manufactured by any company has been so small that it has not been practicable to employ those methods of quantity production which have resulted in such startling reductions in the cost of automobile manufacture. It is likely, however, that the expansion of the industry will, as was the case in the automobile industry, result in very substantial economies in production. The airplane is not inherently a very

complicated machine, mechanically it is distinctly simpler than the automobile, for it has neither transmission nor differential. It is quite reasonable to expect, therefore, that ultimately the cost of an airplane will be no more than that of an automobile of equivalent quality and carrying capacity.

To make flying a profitable commercial undertaking, a low cost of operation is essential. This means not only low consumption of fuel and oil, but also long life and easy maintenance. To reduce wear, means of lubricating all moving parts are provided, and since inspection is such a vital feature of successful operation, the machine is so designed that the condition of all its important parts may readily be observed by the ground crew.

If passengers are to be carried, it is highly desirable that they be made comfortable during their flight. Not only are well-designed seats and good ventilation and light necessary, but certain characteristics inherent in the airplane itself are also required. A moderate degree of stability is essential to safety, but too much may be a source of great discomfort to the passengers in rough air, for it causes the airplane continually to alter its attitude in response to every change of air direction, and so keeps it constantly pitching and rolling.

The most serious discomfort in airplane passenger travel is probably the excessive noise. Since a muffler for the engine exhaust involves both a decrease in engine power and an increase in air resistance, comparatively little has been done toward improvement in this respect. The noise of the engine exhaust is, however, not by any means the only one. The mechanical noises in the engine itself are likely to be of considerable intensity, and the propeller, on account of the high speed with which its tips move through the air, may produce a great volume of sound of most unpleasant quality. Added to these noises are those made by the wind's rushing over all parts of the airplane, though at ordinary speeds of flight these are not very objectionable. When the passengers are carried in a closed cabin, the situation may be much improved by soundproofing the cabin walls though this loses much of its effectiveness if the cabin windows have to be opened in warm weather. A growing appreciation of the importance of the problem may be expected to lead to definite progress toward the ideal of the silent airplane.

The performance required of a commercial airplane depends chiefly on the uses to which the machine is to be put. In the training airplane, which ordinarily flies back and forth over its own field, it is obvious that a high maximum speed is much less important than a low landing speed. In the case of the airplane used for joy riding, high speed again is not very important, since the price obtained for a ride is likely to depend more upon the time spent in the air than upon the distance covered. A machine for this work should, however, have a fairly good rate of climb near the ground, so that it may gain altitude quickly and, even in a short flight, afford its passengers a good view of the country over which they fly.

An airplane employed for ordinary photography is not usually required to have any exceptional performance characteristics, but the machine for photographic mapping is likely to be of a distinctly special type. A series of pictures taken at altitudes of 15,000 or 20,000 ft. is often needed, and the airplane should be able to climb rapidly to its working altitude, so that most of its time in the air may be devoted to producing revenue. It is also necessary, for mapping, that the airplane be able to fly at low speeds, and this, as well as the requirement of altitude performance, means that the wing area must be relatively large. Since photographic mapping is often resorted to for rough country, where landing fields are scarce, it is frequently necessary for the airplane to fly a long distance from its base before picture taking can begin. Under these conditions a high maximum speed is desirable, and it is not surprising that in machines of this class there is a distinct tendency toward the use of engines of higher power, to the improvement both of speed and climb.

In the airplane designed for regular transport service the requirement of speed is paramount. The present schedules of air transport routes in the United States call for ground speeds of about 100 miles an hour. In order to increase engine life, it should be possible to maintain the scheduled speed under reasonably favorable conditions without the necessity of calling on the power plant for its maximum output, and this requirement, together with that of maintaining scheduled ground speed in the face of a head wind, means that the maximum air speed of the airplane must be considerably higher than the required

ground speed. Commercial airplanes are now in use which have maximum speeds better than 140 miles an hour with full load, and it is likely that the future will see considerable increases, both in the maximum speed and in the cruising speed at which the airplane ordinarily flies. Over other than mountainous terrain, the commercial transport airplane ordinarily flies at altitudes of 1,500 to 2,500 ft. It is not essential, therefore, that the ceiling be very high, though a high angle of climb near the ground is desirable so that the airplane may easily get out of a small field. Over mountainous country, however, conditions are entirely different, and on the route across the Rocky and the Sierra Mountains, for example, it is common for altitudes of 14,000 ft. above sea level to be reached. The necessity here for a high rate of climb and a high ceiling seems likely to lead to the use of supercharged engines.

Types of Commercial Airplanes.—Commercial airplanes may be either monoplanes or biplanes. It has already been mentioned that the monoplane is better from the point of view of air resistance for a given lift, while the biplane has the advantage in strength for a given weight. The monoplane appears to be somewhat the better adapted to metal construction, and in recent years there has been a distinct increase in the proportion of monoplanes built, but the biplane is still used in very large numbers, and seems destined to remain a common type. To a certain extent, the choice between monoplane and biplane depends on the personal preferences of the airplane designer and builder.

In the construction of commercial airplanes, wood, metal, or a combination of the two materials may be employed. The present tendency, particularly in the larger airplanes, is toward the all-metal type, and, as metal construction lends itself better to quantity production, this tendency will probably become more evident as the volume of airplane building increases. Smaller airplanes generally have steel-tube fuselages and fabric-covered wooden wings.

Airplanes of small or medium size usually have but one engine, while larger machines may have one large engine or two or more smaller ones. In very large airplanes, the use of more than one engine is obligatory, since aircraft engines of proven types are

not readily available in sizes larger than 600 hp. Improvement in reliability is, however, the chief argument for the multiengine airplane, for if its power loading is not too high it may be possible for a machine of this type to keep on flying and to maintain its altitude even if one engine stops. It must be emphasized that if the full power of all the engines is required for normal flight, then, obviously, if one engine stops the machine will no longer be able to hold its altitude. Under these conditions, the use of more than one engine does not increase reliability, but rather decreases it, since the probability of failure of one engine increases with the number of engines.

The employment of two engines in a commercial airplane which cannot fly on one engine alone is advantageous under special circumstances, such as for long, continuous flights over routes with plenty of landing fields. The airplane may be designed to require the power of both engines to fly with its full load, but still to be able to hold altitude with only one engine if all the fuel is discharged except enough to last to the nearest emergency field. If the field is not too far away, the remaining engine may make possible a long glide to a successful landing without dumping any fuel.

If landing fields are scarce and none of the load is of such nature that it can be dropped in flight, the load must be limited to that with which the machine could fly on one engine. The operation of such an airplane would be very uneconomical.

The case for the use of three engines is distinctly better, for the load which can be carried with two out of three engines is much larger than that which can be carried with only one of two. Unfortunately, however, the three-engine airplane does not really have two-thirds of its thrust power still available when only two engines are running. The loss of speed which results from the decreased propeller thrust with one engine stopped requires the propellers of the two remaining engines to operate under conditions different from those for which they were designed, with consequent decrease in efficiency and reduction in power output. The speed of the remaining engines, moreover, decreases somewhat as the airplane speed decreases, so that their power output is also reduced, and a further decrease in propeller thrust occurs. In order to make effective use of the

gain in reliability to be derived from three engines it is consequently necessary to have considerable excess power available in level flight with all three engines running. This means that the cost and the weight of the power plant and of the airplane are increased over those of the single-engine machine designed to carry the same pay load. The multiengine airplane is also less efficient from the point of view of air resistance. The advantage in reliability is evidently obtained only at the cost of economic disadvantages, but even so, the use of three engines is very often mandatory, especially if the airplane is to carry passengers where opportunities for successful forced landings are infrequent.

If the full benefits of increased reliability resulting from the use of three or more engines are to be obtained, there should be, in so far as is possible, not only separate engines, but separate power plants as well. This applies particularly to the fuel system, and it is essential that this be designed so that the failure of any one part of it cannot possibly affect the operation of more than one engine. It is desirable, also, that the fuel intended for one engine be available for the others, should that engine fail. Separation of lubricating, cooling, and ignition systems, and of engine controls, is, ordinarily, not difficult to arrange.

Even with complete separation of power plants, it must be realized that certain causes of failure, such as poor fuel, overheating, and the formation of ice, may affect all the engines at once, and experience has shown that the three-engine airplane is not entirely immune to forced landings caused by power-plant troubles.

Typical Commercial Airplanes.—To describe every commercial airplane manufactured in the United States, to say nothing of those manufactured abroad, would require far more space than can be given to the subject in a book of this sort, and even to describe one of each type would still require too much space. Among American commercial airplanes, however, three types appear in larger numbers than any others. These are: the small machine for a pilot and one or two passengers in open cockpits; the machine of medium size for the pilot and four or five passengers, in a closed cabin; and the large, three-engine airplane for

two pilots and ten to fifteen passengers. As an example of the first class, the Waco Ten will be described; of the second, the Travel Air monoplane; and of the third, the Ford monoplane.

The Waco Ten is a tractor biplane for a pilot and two passengers, all in open cockpits. It was built originally with the Curtiss OX-5 engine, which was available in large numbers, at a low price, from surplus war stock. This engine is reasonably satisfactory in operation, but is obsolete in design and distinctly heavy in proportion to its power. The airplane is there-



FIG. 175.—Waco Ten with OX-5 engine. (Courtesy Advance Aircraft Co.)

fore manufactured also with the Ryan-Siemens engine, a seven-cylinder, air-cooled radial. The airplane with the OX-5 engine is illustrated in Fig. 175 and with the Ryan-Siemens engine in Fig. 176.

In wing arrangement, the machine is a single bay biplane, with the wings divided into an upper center section, two upper outer sections, and two lower outer sections. The wings are covered with fabric, and have wooden spars and wooden ribs of the truss type, with two false ribs at the nose between each pair of main ribs. The diagonal bracing of the internal drag truss is of steel wires. The interplane bracing consists of tubular stream-

line struts and streamline steel-wire diagonals. The lift wires are double, and the two wires of each pair run to different points on the fuselage, so as to give additional rigidity against drag loads. Four ailerons are used, and these are operated by cranks and tubular push rods, without the use of wires or cables.

The tail surfaces are of conventional design, braced externally by struts and streamline wires. The stabilizer is adjustable, and elevators are operated by concealed levers and tubes. The rudder controls employ the conventional horns and cables.



FIG. 176.—Waco Ten with Ryan-Siemens engine. (*Courtesy Advance Aircraft Co.*)

The landing gear is of the split-axle type, with main members of steel tubes, and is furnished with or without brakes. The shock-absorbing mechanism is of the oleo type.

The fuselage framework, including the diagonal bracing, is made of steel tubes, welded at the joints—a method of construction which results in a rigid structure not likely to get out of alignment.

The fuel and oil tanks are in the front of the fuselage, behind the engine. When the OX-5 engine is used a radiator is mounted under the upper center section, as shown in Fig. 175. This radiator is of conventional type and has shutters for temperature control.

The two passengers are carried in a single large cockpit between the wings, and the pilot rides in a smaller one behind, where he has good vision both upward and downward. Metal cowling is used over the engine and around the cockpit, and fabric for the covering of the rest of the fuselage. The fuselage is of streamline form, except for the irregularities at the cockpits. The water-cooled OX-5 engine is completely enclosed, with short exhaust manifolds on each side. The cylinders of the air-cooled engine are exposed, and in front is a collector ring, into which all cylinders exhaust, and from which a short pipe discharges the gases under the fuselage,* thus minimizing the noise. A heater over this exhaust pipe provides warm air for the carbureter when required.

Airplanes of this type have had a wide sale among private owners and aerial service operators. The characteristics are given in Table V at the end of the chapter.

The Travel Air Model 6,000 is a single engine, semicantilever tractor monoplane of the closed-cabin type, designed for two pilots and four passengers with baggage. A general view of the airplane is shown in Fig. 177, and one of the interior of the cabin



FIG. 177.—Travel Air Model 6,000. (Courtesy Travel Air Manufacturing Co.)

in Fig. 178. The wings are of conventional wood-and-fabric construction, with built up trussed ribs, and box spars with plywood webs. The internal drag trussing employs swaged steel tie rods; the external wing struts are of round steel tubing, streamlined with balsa wood.

The control surfaces have steel frames and are covered with fabric. The stabilizer is adjustable, and dual controls of the

wheel-and-post type are provided, as shown in Fig. 178. The rudder is operated by pedals.

The landing gear is of the split-axle type, with oleo shock absorbers and brakes on each wheel, controlled separately by means of foot pedals which the pilot can operate without taking his feet off the rudder pedals.

The engine is a Wright Whirlwind, fitted with a Standard Steel propeller. The fuel is carried in tanks in the wings, and the



FIG. 178.—Cabin of Travel Air Model 6,000. (Courtesy Travel Air Manufacturing Co.)

oil is in a tank just behind the engine. The total capacity of the fuel tank is 78 gal., and of the oil tank $5\frac{1}{2}$ gal. The engine, engine mount, oil tank, and power-plant instruments are readily removable as a unit to facilitate repairs and adjustments.

The fuselage is built of steel tubing with welded joints, and weight is economized by the use of chrome-molybdenum tubing instead of plain carbon steel. The arrangement of seats and windows is shown in Fig. 178. The cabin is lined inside with plywood and Fabricoid, and the entire fuselage is fabric covered.

Airplanes of this type have found considerable use for regular transport service where the traffic is not too heavy. They have been used also by private owners for the carrying of themselves and their friends, by corporations for saving the time of their executives and salesmen, and to some extent in aerial service and other special work. The characteristics of the airplane are shown in Table V.

The **Ford Model 4-AT** is a three-engine tractor monoplane which carries 2 pilots and 10 to 12 passengers. A general view of this machine is shown in Fig. 179, and one of the interior of



FIG. 179.—Ford Model 4-AT. (*Courtesy Ford Motor Co.*)

the cabin in Fig. 180. The airplane is built entirely of metal, and the construction has already been described in Chap. XII in connection with Figs. 145, 146, 158, 159, 160, and 163. The wing is a pure cantilever and is tapered both in plan and in thickness. It is in three sections, the center one extending across the fuselage from the engine on one side to that on the other. At the center the wing is nearly 3 ft. thick, and has a chord of a little over 12 ft. The entire wing covering is of corrugated duralumin sheet, 0.012 in. thick.

The control surfaces are constructed entirely of metal and covered like the wings. They are conventional in arrangement, and are operated by external horns and cables. The aileron

and elevator controls are of the wheel and post type, and the rudder is controlled by foot pedals. The controls are completely duplicated, so that the machine can be flown by either of the two pilots without the necessity of changing seats. The two control positions, and part of the controls themselves are shown in Fig. 180.

The landing gear is of the no-axle type and has an unusually wide tread, which makes the machine very stable laterally on

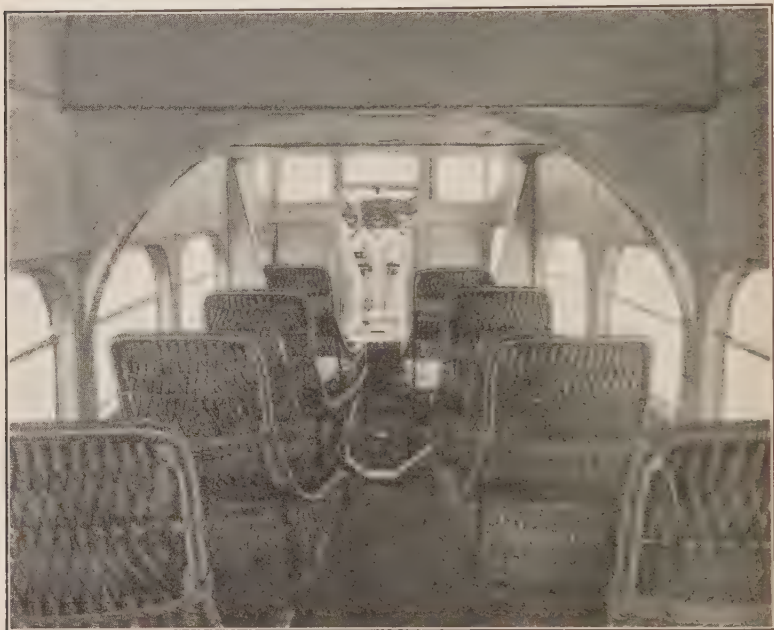


FIG. 180.—Cabin of Ford Model 4-AT. (Courtesy Ford Motor Co.)

the ground. The shock-absorbing mechanism, which is enclosed in the enlarged portion of the vertical struts, consists of a series of rubber disks acting in compression. The wheels are fitted with hydraulic brakes which can be operated by the pilot either separately or together. The combination of brakes and a wide tread makes the airplane unusually easy to handle on the ground, considering its size. The latest models of this type have a swiveling tail wheel instead of a tail skid.

The airplane is provided with three Wright Whirlwind engines, each of which is equipped with a Standard Steel propeller. One engine is in the nose of the fuselage, and the other two are carried under the wing at the extremities of the center section. The fuel is carried in tanks in the wing and feeds by gravity to the engines, and an individual oil tank is provided in the cowling back of each engine. Three complete sets of engine instruments are provided, all easily visible to the pilots. The controls for the three engines, which are between the two pilots, are so arranged that they may be operated separately or together.

The arrangement of the interior of the fuselage is shown in Fig. 180. The pilots are in a separate compartment in front, which is entered by a door from the main cabin. In this compartment, they are completely protected and, at the same time, have excellent vision. The passengers are seated in two rows along the sides of the cabin and can look out through windows under the wings. Toilet accommodations and a space for baggage are provided in the rear. Soundproofing material is employed between the inner and outer surfaces of the cabin, and the noise has been minimized by discharging the exhaust from the center engine under the fuselage, and that from the two side engines above the wings. The cabin is entered by a door at the rear, which may be seen in Fig. 179. The characteristics of this airplane, together with those of the two previously described, are shown in the following table:

TABLE V.—CHARACTERISTICS OF TYPICAL COMMERCIAL AIRPLANES

Name and model	Waco Ten		Travel Air 6,000	Ford 4-AT
Type.....	Tractor biplane		Tractor mono- plane	Tractor mono- plane
Engine.....	Curtiss OX-5	Ryan-Siemens	Wright Whirl- wind	3 Wright Whirlwind
Total rated power, horsepower.....	90	125	200	645
Wing area, square feet..	272	272	282	785
Airfoil section.....	Aeromarine 2A	Aeromarine 2A	Göttingen 398	Ford special
Span, feet and inches...	30' 8"	30' 8"	48' 8"	74' 0"
Length, feet and inches..	23' 11"	23' 11"	30' 6"	49' 10"
Height, feet and inches..	9' 2"	9' 2"	9' 0'	12' 8"
Weight with full load, pounds.....	2,050	2,017	4,000	10,000
Weight empty, pounds..	1,250	1,217	2,350	6,100
Useful load, pounds....	800	800	1,650	3,900
Crew, pounds.....	160	160	170	340
Fuel and oil, pounds....	252	331	480	1,525
Pay load, pounds.....	388	306	1,000	2,035
Wing loading, pounds per square foot.....	7.5	7.4	14.2	12.7
Power loading, pounds per horsepower.....	22.8	16.1	20	15.5
Maximum speed at sea level, miles per hour..	95	115	126	114
Rate of climb at sea level, feet per minute..	425	500	750	
Service ceiling, feet....	13,600	15,000	13,000	14,000

CHAPTER XV

MILITARY AIRPLANES

All airplanes designed for operation in war, whether by the army, the navy, or an independent air force may be included under the term *military airplanes*. With the exception of training airplanes, whose functions are obvious, the chief purpose of most military airplanes is to transport a weapon to the vicinity of the enemy, and to afford a support from which that weapon can be fired when the time of action arrives. In its essentials, such an airplane is merely a firing platform of a highly specialized type.

A military airplane may be intended to attack other aircraft or to attack forces on the ground or on the water, but in any case its essential purpose is the same, and its success depends not so much upon its qualities as a pure airplane as upon its military characteristics. In function, the simplest airplane is that designed solely for the purpose of attacking other airplanes. This type is known as the *pursuit* in the U. S. Army Air Corps, and as the *fighter* in the U. S. Navy. Somewhat broader in its purpose is the *observation airplane*, or *two-seater fighter* employed by the Army Air Corps. It has considerable offensive power, but also has other uses, such as taking photographs, spotting the fall of projectiles, and scouting. Its armament is, therefore, partly offensive, and partly defensive. The *bombardment airplane*, or *bomber*, has two distinct kinds of armament, one of which is designed for offensive purposes against targets on the ground or water, and the other for defensive purposes against other aircraft. Examples of these and other types of military airplanes will be described in the latter part of this chapter.

Only a brief consideration of the descriptions and photographs of these various types of military airplanes is needed to show to what extent the design is dominated by military requirements. Comfort, for example, is quite secondary, and the crew is seldom

carried in any but open cockpits. Appearance is also of little importance, and no effort is spent on any refinements which do not contribute directly to the fighting value of the airplane. The main purpose in the design of the military airplane is to secure the greatest possible effectiveness in the use of the weapons which the airplane carries. The problem is not one of installing guns or bomb gear in an airplane, but rather one of building an airplane around the armament. Every effort is made to secure a good field of fire from every gun, and wherever possible enough guns are provided so that there is no direction from which an enemy can attack without coming under fire. Great attention is paid to securing a good field of vision for all members of the crew. In an airplane designed purely for offensive purposes, such as the single seater, vision and maneuverability are paramount, since the guns can be fired only straight forward.

In every military airplane, performance is of the greatest importance, but different performance characteristics are important in different types of airplanes. In pursuit airplanes, for example, maneuverability, speed, and climb, particularly at high altitudes, are an evident necessity, and great endurance and economy of fuel consumption are not. In the bombing airplane, to go the other extreme, neither high speed nor a high performance at altitude is by any means as necessary as long range and great lifting capacity. Reference to Table VI, at the end of the chapter, will show how wide are the variations in these respects among different types of airplanes.

While military airplanes are designed to be as safe as possible in operation, this consideration cannot be given the same weight as it is in designing commercial machines. Increased safety, and particularly greater structural strength, cannot be had without an increase in weight and a consequent reduction in performance. As its performance is reduced, the airplane becomes less effective as a fighting machine, and so is more likely to be defeated in combat, with the result that the crew of a very safe airplane of low performance is really worse off than that of a less conservative machine of high performance. It should be understood, however, that for similar maneuvers the military airplane almost always has a greater margin of safety than a corresponding commercial type; the difficulty is that the military

machine must perform evolutions which make higher demands upon its structural strength than any which a commercial airplane is likely to have to execute.

The design of a military airplane is distinctly a harder problem than that of a commercial machine, for a military airplane must often be required to fulfil several rather different functions. The observation airplane, for example, must have speed, climb, and maneuverability enough to give it a reasonable chance of success in an encounter with a pursuit airplane, while at the same time it must be able to carry a large camera, a radio set, or a number of bombs. Not only is it a perplexing task to find space for these installations, but it is also difficult to prevent part of the equipment from interfering with the operation of the others. The pilot's guns occupy a space which would also be very desirable for instruments. The bomb-release handles may interfere with the stabilizer adjusting wheel, and the ammunition holders may occupy just the location where the radio controls might best be placed. On the other hand, if an airplane can perform only one function, then the number of machines required to carry out all the duties which may be required of an air force is considerably increased, and if resources are limited, some functions may not be well provided for. Obviously, a compromise is necessary, for the highly specialized design has but limited utility, and that intended for a multiplicity of functions is less effective in any one of them.

To a certain extent, cost is a secondary feature in military airplanes, for in time of war considerations of economy are thrown to the winds. It is highly desirable, however, that military airplanes be easy of manufacture, both to reduce the time required to equip an air force after the outbreak of hostilities, and also to furnish the large number of replacements needed to maintain it at full strength. Since the easily manufactured airplane is likely also to be one low in cost, the military airplane should be designed to be as cheap as possible without sacrificing any essential characteristics. Obviously, also, such an airplane must be constructed from materials available at home, so that quantity production in time of war may not be hampered by interruptions in foreign commerce.

With these considerations in mind, let us discuss specific examples of various types of military airplanes.

The Training Airplane.—The airplane in which the student receives his first instruction differs materially from other military airplanes because it ordinarily carries no weapons. The first requisite in such a machine is ease of handling, so that the student may learn to fly without undue difficulty, but the airplane must not be too easy to fly, lest the student who has learned on it be unfit to pilot airplanes less easily managed. As the machine is subjected to hard use, it must be robust in construction, and should be put together in such a way that damaged parts can



FIG. 181.—Consolidated PT-1 training machine. (*Courtesy Materiel Division, U. S. Army Air Corps.*)

be replaced with the least possible labor and delay. Good vision for both members of the crew is essential, because the student needs all the vision he can get, in any case, and because training airplanes are often operated in large numbers over a relatively small area. Performance is a relatively secondary consideration, so long as it is good enough to give the student somewhat the same sensations as those he will later experience in service machines.

The Consolidated PT-1, illustrated in Fig. 181, is now a standard U. S. Army Air Corps primary training machine. The wings are of wood, covered with fabric, and the fuselage is built

of welded steel tubing, as are also the landing gear and the framework of the control surfaces. The landing gear is of the split-axle type, with rubber shock absorbers. Very little attention has been paid to streamlining, since, as has already been mentioned, it is more essential that a training airplane should be cheaply constructed than that it should have a high performance. The engine is almost entirely exposed, so that the inspection and maintenance work required to keep it running well may be carried out with the least possible labor and delay.

The machine is a conventional single-bay biplane with considerable stagger. The *wing skids*, the curved members underneath the wing tips, are to prevent injury to the wings in case the airplane heels over on the ground. Large cockpit openings are provided both for the purpose of improving vision, and to make it easy to leave the airplane in case of difficulty. The instructor rides in the front cockpit. Each cockpit has a full set of controls, but only the instructor has a complete set of instruments, since the student usually has little time to spare to see how the power plant is operating.

The airplane was designed for the 180-hp. Wright-Hispano water-cooled engine, which the Air Corps had available in considerable numbers. This engine can, however, be easily replaced by the air-cooled Wright Whirlwind if desired. To secure more room in the fuselage, and to reduce the danger of fire in a crash, the fuel is carried in two tanks in the upper wing, from which it runs by gravity to the engine. The radiator is in front, below the engine, and the reserve water tank can be seen in the illustration above the engine just behind the propeller. The dimensions, weight, performance, and other characteristics of the airplane are given in Table VI.

The Pursuit Airplane.—The pursuit airplane is, as already mentioned, purely an offensive type and depends for its effectiveness almost wholly upon high performance and great maneuverability. Not only must it have high speed at the ground, but it must also have a high rate of climb and still retain its speed, maneuverability, and climbing ability at altitudes of 15,000 ft. or greater, for it is at these altitudes that pursuit combats may be expected to take place in modern warfare. Pursuit machines are almost always quite small, but have large power plants in

proportion to their size. Provision is often made for carrying a radio set or a number of small bombs, but the principal item of equipment consists of two fixed machine guns which always point straight forward. To permit the guns to fire through the propeller, an interrupting mechanism is installed which prevents the gun from firing when a propeller blade is in the path of the bullets. Good vision in all directions is absolutely essential, for the pilot has no one but himself to depend upon to detect the approach of hostile aircraft. The pursuit airplane is not designed



FIG. 182.—Curtiss P-2 pursuit airplane. (*Courtesy Materiel Division, U. S. Army Air Corps.*)

for long flights, because this would require carrying so much fuel as to impair the performance and maneuverability.

Most army pursuit airplanes in the United States have been equipped with water-cooled engines, as have the majority abroad. In Great Britain, however, air-cooled engines have found wide use in this class of airplane, and it appears likely that other countries will soon adopt this type of power plant.

The standard pursuit airplane of the U. S. Army Air Corps at present is the Curtiss P-2, shown in Fig. 182. This is a single-bay tractor biplane, with considerable stagger, so that the pilot can be seated behind the trailing edge of the upper wing in a location

where his vision is comparatively little interfered with. The lower wing is considerably smaller than the upper both in span and in chord, so as to offer as little obstruction as possible to the pilot's vision downward. To avoid the structural disadvantages of sloping the lift trusses backward, the rear lift wires are connected to the fuselage at the lower front wing hinge, and the front lift wires pull from a point ahead of this on the lower longeron. This arrangement of bracing is apparent on close inspection of the picture. It is impossible to have a landing wire for the front truss, and accordingly only the rear truss is complete to the extent of having a landing wire as well as a lift wire. The interplane struts seen from the side are arranged in the form of the letter N. The single strut behind them connects the upper and lower ailerons. The wing panels are tapered, and have wooden box spars, wooden ribs of the truss type, and aluminum leading-edge reinforcements extending from the top of the front spar around the leading edge and back to the bottom of the spar. The control surfaces all have metal frames and are covered with fabric. The landing gear is of the split-axle type, and the shock absorbers are rubber disks acting in compression, which are placed inside the fuselage to reduce air resistance. The fuselage is constructed entirely of welded steel tubing with wire diagonals. It is covered with fabric except around the engine and cockpits, where sheet-aluminum cowling is used.

The airplane is equipped with the Curtiss V-1400 engine. The radiator is of the cartridge-core type, placed under the engine, with an expansion tank above. The main fuel tank is behind the engine, and an auxiliary tank is hung under the fuselage at the center of gravity. The presence of this tank naturally reduces the performance of the airplane, so it is designed to be dropped when an enemy is encountered. The regular armament consists only of two machine guns firing forward, but provision is made for carrying light bombs which may be used for attacking troops on the ground. Reference to Table VI will show that in comparison with other airplanes the performance of the pursuit type is distinctly high. Wing loading is moderate, and the power loading is low, so that speed, climb, and ceiling are all very good.

The development of pursuit airplanes is being actively carried forward in all countries and, consequently, pursuit airplane performances are steadily improving. It is quite likely that the adoption of supercharged engines will soon make possible speeds of 200 miles per hour, together with service ceilings of 30,000 ft. or more.

The Observation Airplane.—The observation airplane, sometimes called the two-seater fighter, is designed to be formidable both offensively and defensively. Its performance, while not



FIG. 183.—Curtiss O-1 observation airplane. (*Courtesy Materiel Division, U. S. Army Air Corps.*)

quite as good as that of the single-seater fighter, is still better than that of almost any other type of airplane. It is equipped with a high-powered engine, and as it is not usually a very large airplane, its maneuverability is inferior only to that of the small pursuit machine. This inferiority in maneuverability and performance is, to some extent, offset by the addition of two guns on a swivel mount which can fire in almost any direction, and are operated by the second member of the crew. The pilot is provided with the same guns as in a pursuit machine. This makes the airplane distinctly a formidable opponent, and some authorities consider it to be the equal of the pure pursuit type. In addition to this armament, provision is made for carrying

bombs in a moderate amount, so that if need be such a machine may be used for bombardment. It can carry an elaborate camera equipment, and so may be employed for taking photographs of enemy troops or works. In addition to this, it carries a radio set, so that the results of observations can be quickly reported.

A typical observation airplane, the Curtiss O-1, is shown in Fig. 183. This is a single-bay tractor biplane of conventional design, except that the upper wing has a considerable sweep back to afford good vision combined with correct balance. There is therefore a much greater stagger at the center section than at the wing tips. The arrangement of lift trusses is like that already described in connection with the Curtiss P-2. The wings have wooden box spars, wooden trussed ribs, and duralumin fittings. The leading edge of the wing is reinforced by a sheet of aluminum. The control surfaces have metal frames with fabric covering, and the stabilizer is adjustable from the pilot's seat. The landing gear is of the split-axle type; in some of these airplanes oleo shock absorbers have been used, and in others rubber disks in compression. From the cockpits forward, the fuselage is of welded steel-tube construction without wires, while behind the cockpit duralumin tubing is used with riveted joints.

The engine ordinarily used is the water-cooled Curtiss D-12. A radiator of the cartridge-core type enclosed in a cowl is installed below the engine, as shown in the photograph. The fuel is carried in tanks in the fuselage behind the engine.

The pilot, who rides in the forward cockpit, has two guns firing forward, as already mentioned. The gunner, who is in the rear cockpit, has a complete set of airplane and engine controls for an emergency. The stick may be detached and fastened out of the way so that he may move freely about the cockpit when he is not flying the airplane. His seat folds out of the way when not in use. The illustration shows the flexible mount upon which his two machine guns are carried. The radio and camera are inside the fuselage, and the bombs are carried underneath. The performance of this airplane is given in Table VI, and it will be apparent that in spite of its heavy load, its speed and climb compare fairly well with those of pursuit airplanes, and are distinctly better than those of airplanes of any other class.

The Bombing Airplane.—The primary purpose of bombing airplanes is the destruction of the enemy on the ground. The bombardment airplane, therefore, being designed to carry a heavy load over a relatively long distance, is comparatively large and slow, and distinctly inferior in speed, climb, and maneuverability to the types previously discussed. All the guns of a bombing airplane are on flexible mounts, as fixed guns would be useless on a machine of so little maneuverability. These guns, however, are strictly for defensive purposes, and a bombing airplane would seldom attempt to engage in combat



FIG. 184.—Keystone LB-5 bomber. (*Courtesy Materiel Division, U. S. Army Air Corps.*)

with another machine unless first attacked. Its business is to proceed to its assigned objective, drop its bombs, and return as quickly as possible.

As the power required for a modern bombing airplane is large, two engines are often used, and by carrying them on the wings, one on each side of the fuselage, the bomber who rides in the front of the fuselage is afforded better vision downward and forward for operating his sights than he would have if there were an engine in front of him.

As an example of an American bombing airplane, the Keystone LB-5 is illustrated in Fig. 184. The machine is a single-bay

biplane with equal upper and lower wings, both of which are tapered. Wings and tail surfaces are of conventional construction, with internal framing of wood, covered with fabric. The fuselage structure is of welded steel tubing. There are three sets of vertical tail surfaces, as may be seen in the photograph. The landing gear has an unusually wide tread, and is so arranged as to offer no obstruction directly below the fuselage. Oleo shock absorbers are used. Another advantage of the arrangement of landing gear used on this airplane is that in landing the weight of the engines is transmitted directly to the wheels, so that the wings are entirely relieved of this large load.

The power plant consists of two Liberty engines, each in a separate nacelle. Radiators are of the conventional cartridge-core type, mounted under the engines.

In the extreme nose of the fuselage is a position for a machine gunner operating two Lewis guns on the same swiveling mount. Below this position is that of the bomber, who sights his objective through windows in front. Here are also the bomb release controls so that he can drop the bombs at the correct moment. The normal bomb load of six 300-lb. bombs is carried in a compartment in the center of the fuselage. Just in front of the wings are the seats for the two pilots, and behind the wings is a position for another machine gunner, who has two guns on a swivel mount, and a third which fires through an opening in the floor. The radio operator, the fifth member of the crew, is in a separate compartment near the rear gunner. With its normal load, the airplane has a cruising range of 400 miles. Other data on this machine may be found in Table VI.

The Navy Fighter.—In order to defend surface ships against aerial attack, and to protect other airplanes carrying out bombing or scouting missions for the naval forces, it is essential that every naval fleet be provided with a considerable number of fighting airplanes. These machines are of much the same type as the Air Corps pursuit airplanes. They may be equipped with floats for landing on the water, though a wheel-type landing gear is more common, to permit them to be launched from and return to the deck of an aircraft carrier. Navy fighters are generally equipped with air-cooled engines instead of with the water-cooled type, because while the use of the air-cooled engine

may involve some loss in high speed, it makes possible a better rate of climb, and also offers the advantage of a much shorter warming up period between the time when the engine is started and the time that it is ready to be run at full power. The air-cooled engine is shorter than the water-cooled engine and so saves space in the fuselage, with a resultant reduction in the overall length of the airplane.



FIG. 185.—Curtiss F6C-4 navy fighter. (Courtesy Bureau of Aeronautics, U. S. Navy.)

A typical example of the Navy fighter is the Curtiss F6C-4, which is illustrated in Fig. 185. In structure this airplane is almost the same as the Curtiss P-2 Air Corps machine already described. It is equipped, however, with the Pratt & Whitney Wasp engine instead of with the Curtiss V-1400. A comparison of the performance figures for the two machines shows that in spite of the lower power of the air-cooled engine, the F6C-4 is inferior to the P-2 only in high speed at sea level. When the airplane is operated from a carrier, the landing gear must be provided with several special devices, which, in connection with certain apparatus on the deck of the ship, permit it to be landed with a very short run after it touches the deck. If the airplane has the float-type landing gear it can be launched from a ship

with a catapult. This catapult is a device which consists of a car upon which the airplane is mounted, driven by powder or compressed air along a track which can be pointed into the relative wind. At the end of its run, the airplane is released with a speed sufficient to enable it to fly under its own power. Like its army prototype, the F6C-4 is armed only with two machine guns firing forward through the propeller. The performance is given in Table VI.

The Three-purpose Airplane.—The Navy employs observation airplanes much like those of the Air Corps, and in addition another type somewhat different from any in the Army. This is the *three-purpose airplane*, which may be used for bombing, torpedo dropping, or long-distance scouting. Such an airplane may be equipped with wheels to operate from a carrier ship, or else with floats with which it can take off from and land on the water. Alternatively, it may be launched from a catapult and be hoisted aboard the ship again after landing in the water alongside. When used for scouting, these airplanes can take an extra large supply of fuel, but when a bomb or torpedo is carried the fuel tanks are not completely filled. Tactics in bombing are much the same as those employed by Air Corps bombardment machines. In dropping a torpedo, however, it is necessary for the airplane to come down within 10 or 15 ft. of the water, as otherwise the delicate controlling mechanism of the torpedo would be damaged by the fall, and its course after being launched would be erratic. A large ship provided with antiaircraft guns is attacked simultaneously by several machines from different directions, under the supposition that it would not be possible for the defenders to bring down all of them before one or two had delivered their torpedoes.

An example of the Navy three-purpose airplane is the Glenn Martin T3M-2, which is illustrated in Fig. 186. This is a single-bay tractor biplane, with equal upper and lower wings. The wing is of conventional wood and fabric construction. The control surfaces have metal frames, and are covered with fabric, and the fuselage is of welded steel tubing. The landing gear consists of two separate structures, each provided with an oleo shock absorber and supporting a wheel. This land-type landing gear can readily be replaced by one of the twin-float

type. The engine is a Packard 3A-2500, installed in the nose and provided with a three-blade Standard Steel propeller. The radiators are mounted beside the fuselage, between the wings; one of them is visible in the photograph. The front cockpit is for the bomber, that just behind for the pilot, and the third, some distance to the rear, is for the gunner, who operates two Lewis machine guns on a flexible mount. The torpedo is carried under the center of the fuselage, as shown in the photograph. This may be replaced by a 2,000-lb. bomb or by an equivalent weight



FIG. 186.—Glenn Martin T3M-2 three-purpose airplane. (*Courtesy Bureau of Aeronautics, U. S. Navy.*)

in smaller bombs. The performance of this airplane is given in Table VI, and should be compared with that of the Keystone LB-5.

The Navy Patrol Airplane.—A distinct type of naval airplane which has no Air-Corps prototype is the patrol airplane. This is a large flying boat, and is so seaworthy that it can go to sea and remain afloat for long periods without having to be hoisted out. It can operate from shore bases for coast patrol, but in modern American practice is more often part of the fleet. These machines do not ordinarily land in the open sea unless forced to do so, and they would not remain afloat indefinitely in rough

weather, but so long as they can make their flights between harbors they can operate for several months with no more attention than they receive from a mother ship. They can carry large quantities of fuel, and single flights of a thousand miles are not uncommon, but in other respects their performance is not high.

The PN-10, which is illustrated in Fig. 187, is an example of the type. The photograph shows the boat hauled out on a handling truck. The wing truss has only a single bay outside the engine, with some overhang, and dihedral only on the lower



FIG. 187.—PN-10 flying-boat. (*Courtesy Bureau of Aeronautics, U. S. Navy.*)

wings. The wing structure is of wood and fabric, and the control surfaces have fabric covering over metal frames. The hull has duralumin framing and is covered entirely with duralumin sheets with riveted joints, a type of construction which has been found very seaworthy. The fact that it does not increase in weight by soakage recommends the all-duralumin hull, particularly for flying boats which are moored out for long periods.

The power plant consists of two Packard 1A-1500 engines, mounted between the wings. Each engine drives a three-blade, tractor, Standard Steel propeller. Two cartridge-core radiators directly behind the propeller are provided for each engine. Oil is carried in tanks in the nacelles. Some of the fuel is carried

in tanks in the upper wings, but most of it is in the hull, from which it has to be pumped to the wing tanks.

Two positions for machine gunners are provided, one in the extreme nose and one behind the wings. A powerful radio set is carried, so that reports of observations can be sent back promptly to the fleet from which the airplane is operating. The machine has an endurance at full speed of $11\frac{1}{2}$ hours and a range at cruising speed of slightly over 1,600 miles. The other figures on its performance are given in the following table.

TABLE VI.—CHARACTERISTICS OF TYPICAL MILITARY AND NAVAL AIRPLANES

Builder	Consolidated	Curtiss	Curtiss	Keystone	Curtiss	Glenn Martin	Naval Aircraft
Model	PT-1	P-2	O-1	LB-5	F6C-4	T3M-2	PN-10
Type	Air Corps training	Air Corps pursuit	Air Corps observation	Air Corps bombing	Navy fighter	Navy torpedo	Navy patrol
Engine	Tractor biplane Wright E	Tractor biplane Curtiss V-1400	Tractor biplane Curtiss D-12	Tractor biplane Two Liberty	Tractor biplane P. & W. Wasp	Tractor biplane Packard 3A-2500	Tractor biplane Two Packard 1A-1500
Total power, horsepower	190	500	450	850	425	730	1,000
Span, feet and inches	34' 9½"	31' 7"	38' 0"	66' 6"	31' 6"	56' 7"	72' 10"
Length, feet and inches	27' 8"	22' 10"	28' 4"	45' 0"	22' 6"	41' 4"	49' 2"
Height, feet and inches	9' 0"	8' 6½"	10' 1"	16' 6"	9' 8"	15' 2"	16' 8"
Wing area, square feet	283	250	350	1,138	252	848	1,217
Airfoil	USA-27	Clark Y	Clark Y	USA-45	Clark Y	USA-27	USA-27
Weight loaded, pounds	2,550	2,869	4,165	11,990	2,714	9,249	18,994
Weight empty, pounds	1,805	2,081	2,417	6,848	1,964	5,545	10,060
Useful load, pounds	745	788	1,748	5,142	750	3,704	8,934
Wing loading, pounds per square foot	9.2	11.5	11.9	10.5	10.8	10.9	15.6
Power loading, pounds per horsepower	13.5	5.7	9.3	14.1	6.4	12.7	19.0
High speed, sea level, miles per hour	99	172	143	108	162	108	114
Climb in 10 min., feet	8,200	14,200	8,400	3,400	14,700	3,300	2,500
Service ceiling, feet	13,500	23,000	17,400	8,000	22,900	7,800	4,500

CHAPTER XVI

SPECIAL TYPES OF AIRPLANES

It has already been pointed out that in designing an ordinary airplane compromises must be made to get the best combination of all the desirable characteristics, without neglecting or over-emphasizing any of them. Even in the design of a pursuit machine, which is a fairly close approach to a pure type, other considerations than high performance must be given weight. The installation of guns leads to modifications in the shape of the fuselage, and the requirement of good vision for the pilot involves alterations in the arrangement of the wings, with the result that to some extent performance is subordinated to military effectiveness. The design of a commercial airplane ordinarily necessitates even greater compromises. Here, speed and climb must be sacrificed to economy of operation, and all of these must give way to safety and reliability, and to some extent also to considerations of passenger comfort, accessibility, and easy maintenance.

The compromise types of military and commercial airplanes having been described in the two previous chapters, it is of interest now to devote some attention to airplanes of special types intended primarily to accomplish some particular feat, or else reconstructed from conventional airplanes to emphasize certain characteristics at the expense of others. The extent to which this may be carried is illustrated by the familiar *Spirit of St. Louis* used by Colonel Lindbergh. In this airplane, the vision was cut down to a point wholly insufficient for an ordinary pilot, in order to give room for a large fuel tank so located as not to disturb the balance of the airplane or crush the pilot in a forced landing. Such an arrangement would not be tolerated for a moment in a commercial machine, but was quite justifiable in this case as a means of making possible the attainment of a particular objective. Since special airplanes are designed

each for one rather limited purpose, it is not surprising that for that purpose they are vastly superior to other airplanes, though in general characteristics they are likely to be inferior to machines of conventional design, and so find only limited fields of usefulness.

There are so many sorts of special airplanes that it would be quite out of the question to describe all of them. Three, however, are of particular interest, because they represent three different extremes; these are the high-speed airplane, the long-range airplane, and the high-altitude airplane.

The High-speed Airplane.—The true racing airplane is designed primarily for speed and other characteristics are given little consideration except as they contribute to victory in the contest for which the machine is intended. Reference to the chapter on Airplane Performance will recall that speed depends upon two factors: power required and power available. In the high-speed airplane, therefore, the endeavor of the designer is to make the power available a maximum and the power required a minimum. Reduction in power required is obviously to be attained by reduction in drag, and to this end every part of the airplane exposed to the wind is made as small and as smooth as possible, and many parts which in the ordinary airplane are in the open are here concealed. Since the wings account for a large part of the resistance, their area is often reduced to the smallest consistent with a stalling speed which is not so high as to make landing unduly difficult for a skilled pilot, and this limit in stalling speed is frequently in the neighborhood of 100 m.p.h. The fuselage of the racing machine is just as small as circumstances will permit, and the very minimum of external bracing is used on wings, landing gear, and tail. To cut down resistance still more, even the vision of the pilot may be sacrificed to an extent which would not be at all allowable in ordinary airplanes. On account of the high air velocities over the control surfaces of racing machines, the changes in force for small movements of the controls are very great, and flying a racer is such a delicate operation that it can be entrusted only to pilots of the highest skill.

For the power plant of a racing machine, a high-speed, water-cooled engine of great power is almost invariably employed,

since an engine of this type has a relatively small frontal area and offers the least obstacle to a good streamline form at the nose of the fuselage. The radiators of modern racers are of the surface type described in Chap. IX. A metal propeller of high efficiency is the universal choice, and gearing is often employed to permit an increase in engine speed and power output.

An excellent example of the modern racing airplane is the Supermarine S.5 seaplane, in which Flight-Lieut. S. N. Webster, R.A.F., won the Schneider Cup Race on Sept. 26, 1927. This machine is shown afloat in Fig. 188 and hauled out on a handling

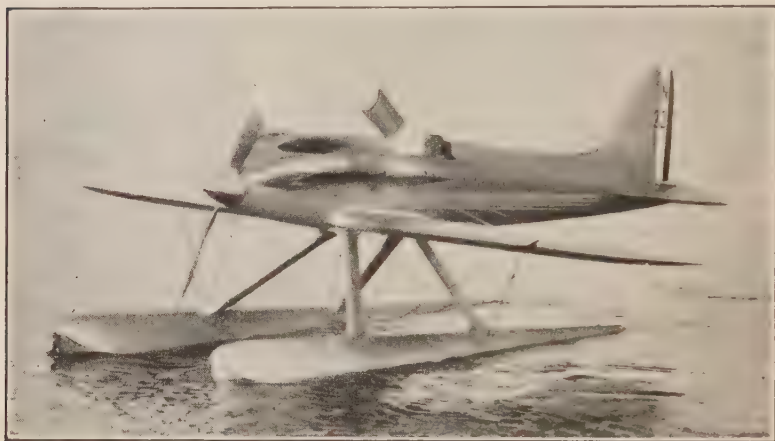


FIG. 188.—Supermarine S.5 seaplane afloat. (*Courtesy Supermarine Aviation Works, Ltd.*)

truck in Fig. 189. From the latter photograph particularly, the cleanness of the design and the extent to which all unnecessary resistances have been eliminated is very apparent. The wings are constructed of wood with two spars and ribs of normal type, and an additional stiffening member is introduced toward the tip to prevent flutter. The covering is entirely of plywood, a common practice on racing airplanes, as fabric is altogether too likely to be torn off. The plywood cover is necessary also to provide an adequate support for the radiators. For external wing bracing only streamline wires are used.

The fuselage of the S.5 is built entirely of duralumin with the exception of some steel fittings. The skeleton consists of transverse formers with longitudinal stiffeners, and the skin, thus

supported by the interior framework, is able to carry a considerable portion of the load. The cross-section of the fuselage is so small that the pilot is obliged to sit on the floor with his shoulders touching the skin on each side. A hinged cover, which is plainly visible in the open position in Fig. 188, encloses all the cockpit except a space just large enough for the pilot's head.

The floats are built entirely of duralumin, except for part of the one on the right, which is made of steel and forms a fuel tank.

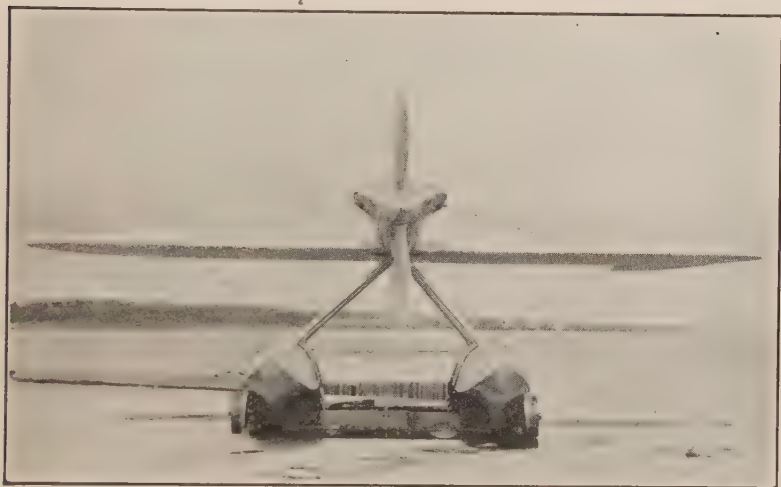


FIG. 189.—Supermarine S.5 seaplane on handling truck. (*Courtesy Supermarine Aviation Works, Ltd.*)

The float bracing consists of four struts and a system of streamline wire transverse and diagonal bracing which is quite clearly shown in Fig. 188. It should be noted that since the wing lift wires run to the float, and the antilift wires to the top of the fuselage, it is possible to reduce air resistance by substituting wires for the struts which ordinarily have to be employed between the floats.

The control surfaces have wooden frames covered with plywood like the wings—a construction so strong that no external bracing is required, and this item of resistance is eliminated.

The power plant is the special racing type Napier Lion engine, illustrated in Fig. 94 (p. 129). Its characteristics have already been given in Table IV.

The engine drives through a reduction gear a two-blade duralumin propeller of the Reed type. Figure 189 shows how smoothly the three cylinder banks of this engine are streamlined into the fuselage. The wing-surface radiators are smooth on their outer surface, so that they involve no additional resistance whatever, a design which constitutes a distinct step forward from the corrugated outer surfaces previously employed. Details of the construction of the Supermarine radiators are still confidential. As the fuselage is too small to contain a fuel tank of the necessary capacity, the fuel is carried in the right-hand float, from which it is raised by a pump to a small tank just behind the right-hand cylinder block. This tank contains enough fuel to keep the engine running if the main supply is momentarily cut off, as may occur on account of the large centrifugal force which is set up when a turn is rounded at high speed. Because of the great power of the engine and the use of gearing, the lubricating oil must be cooled, and for this purpose it is circulated through radiators on the sides of the fuselage. These are of such shape as to offer little air resistance.

Complete and definite information regarding the performance of the S.5, has been kept confidential by the British Air Ministry, for whom it was constructed. As the average speed of the airplane around a comparatively small triangular course for a total distance of about 215 miles was 282 m.p.h., it would not be surprising if the speed on a straight course over a short distance were over 300 m.p.h. The stalling speed is not known, but must be high, for the wing loading is 28 lb. per square foot, and the airfoil section has a distinctly convex lower surface. The total wing area is only 115 sq. ft., and the weight of the airplane loaded is about 3,200 lb.

The Long-range Airplane.—The problem of the long-range airplane is one of carrying a large load of fuel, and at the same time getting the greatest number of miles per gallon consumed. In airplanes of this type, as in racing airplanes, the lowest possible power required is essential, but in racers it is power required at high speed which is important, while in long-range

machines the emphasis is on minimum power, which is found at speeds not much above stalling, as explained in Chap. X. It is not possible to reduce the power required by cutting down the wing area nor by using a wing of low maximum lift coefficient, for either of these procedures would make it impossible to get the airplane off the ground with a heavy load. It is, therefore, considered best to employ a wing of fairly liberal area, moderately high maximum lift coefficient, and good L/D ratio, and at the same time to try for a high aspect ratio and the least possible parasite resistance. Good controllability is essential, for when the airplane is heavily loaded the margin of control is relatively small, and any serious inadequacy in this respect may lead to a crash. Ease of control is necessary also in order not to fatigue the pilot under conditions which at best are very trying. It is obviously desirable that the structure of the airplane should be as light as is consistent with sufficient strength, for every pound saved in the dead weight means just that much more lift available for carrying fuel. At the beginning of the flight, the load is frequently the absolute maximum that can be lifted off the ground, and the problem of carrying this load without throwing the airplane seriously out of balance is often a most difficult one. It is very desirable that the balance be correct both with the tanks full at the beginning of the flight and with them empty at the end, and to ensure this it is evident that the tanks must be placed so that the center of gravity of the fuel is substantially at the center of gravity of the complete airplane. On account of the space necessary in front for the pilots and their controls, however, the fuel usually has to be carried somewhat back of the airplane center of gravity, so that the machine is tail heavy at the beginning of the flight. To a certain extent this condition can be corrected by the use of an adjustable stabilizer, but if a considerable lift load has to be carried on the tail, additional drag will result, and the stability may be impaired.

In the power plant of the long-range airplane, light weight, great reliability, and low fuel consumption are all of the utmost importance. It is not enough for the fuel consumption to be low at full throttle, for the engine is operated at full power only at the beginning of the flight, and as fast as the weight is reduced by consumption of fuel the engine is throttled down, until at the end

of the flight it may be giving only one-fifth of its full power. This means, therefore, that the best engine from the point of view of fuel economy is that which has the best average fuel consumption over a wide range of power output.

A good example of the modern long-range and long-endurance airplane is the Stinson Detroit monoplane illustrated in Figs. 190 and 191, with which Edward A. Stinson and George W. Haldeman broke the world's endurance record in a flight of 53 hours, 36 min., which ended on Mar. 30, 1928. This airplane was not designed primarily to break the record, but rather for the purely commercial function of carrying a good load at a reasonable speed with an engine of moderate power. It therefore had many of the basic characteristics necessary in a long range



FIG. 190.—Stinson Detroit. (*Courtesy Stinson Aircraft Corp.*)

airplane, particularly low power required and low fuel consumption. The Stinson Detroit is a semicantilever, tractor monoplane, with a Wright Whirlwind engine. The wings are of the conventional two-spar construction, fabric covered, with spars of spruce, and ribs stamped from sheet duralumin. The control surfaces are built of welded steel tubes, and are covered with fabric. The external wing bracing consists of a pair of steel-tube struts on each side, with a screw adjustment at the bottom to ensure the correct angle of incidence. Ailerons and elevators are operated by tubes, while the rudder is controlled by the conventional horns and cables. An interesting feature of the tail surfaces is that the fin is set slightly off center to neutralize the effect of slip-stream rotation and so relieve the pilot of the necessity of holding the rudder over. The fuselage skeleton is built of welded chrome-molybdenum steel tubes. Much of the

detail of the structure is visible in Fig. 191, which shows also the interior arrangement of the cabin, with the equipment for the endurance flight. The large fuel tank forms a seat for the pilots. The oil is carried in a tank at the base of the engine mount. Dual controls are provided so that the pilots will not have to change places in relieving each other. One of the control wheels is visible in the figure, below the windshield and behind the instrument board, and the rudder pedals may be seen beneath.

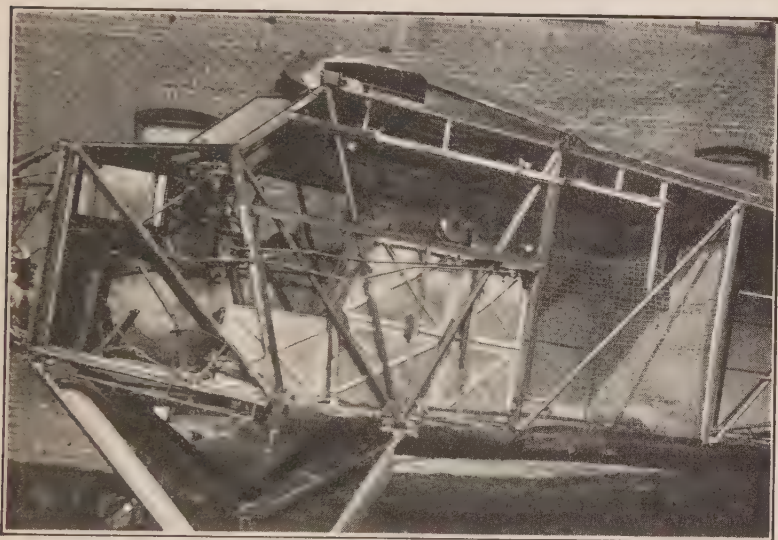


FIG. 191.—Installation of tanks, controls, and instruments in Stinson Detroiter.
(Courtesy Stinson Aircraft Corp.)

The airplane empty weighed 1,970 lb., and when it took off on the record flight it was carrying a useful load of 4,247 lb., of which 3,348 lb. consisted of fuel. About 185 gal. were carried in the large tank shown in Fig. 191, and the rest was in 38 5-gallon cans which were stowed in the cabin wherever space was available. The fuel in these cans was poured into the main tank as fast as needed, and the empty cans thrown overboard. The rest of the useful load, 900 lb., was made up of oil, water, food, special instruments, the 38 cans, and the two pilots and their clothing. It will be noted that the weight of the useful load is more than twice that of the empty airplane, a most unusual ratio.

In order to carry more fuel, the machine was lightened by leaving off the brakes, the exhaust collector, and some of the interior trim. The airplane has a length of 32 ft. 10 in., a span of 45 ft. 10 in., a height of 9 ft. 0 in., and a wing area of 292 sq. ft. The airfoil section employed is the M-6, which was developed by the National Advisory Committee for Aeronautics.

The High-altitude Airplane.—Reference to the discussion of airplane performance in Chap. X will recall that the ordinary airplane, in attempting to climb to a high altitude, encounters two fundamental difficulties: a continuous decrease in power available from the engine, and, on account of the increase in speed necessary to maintain a given angle of attack, a steady rise in minimum power required. These two factors combine to limit the ceiling. The object of the designer of the high-altitude airplane is, therefore, to increase the power available at altitude, and, in so far as is possible, to reduce the power required. Every effort is made to keep down the weight of the airplane, and also to give it the largest practicable wing area, for a large area permits the airplane to maintain flight at a lower speed and angle of attack, and so reduces the minimum power required. In addition, the aspect ratio is made as high as possible, so as to decrease the drag for a given lift, and parasite resistance is minimized to as great an extent as the other limitations of the problem permit. All these reductions in power required leave more excess power for climb.

It will be remembered that the high-speed airplane has a low power loading and a high wing loading. The long-range airplane, at least at the start of its flight, has a high wing loading, and also a high power loading. The high-altitude machine, in distinction to these two, has both a low power loading, and a low wing loading.

While the various measures adopted for reducing the power required do result in a distinct improvement in the performance of the airplane at high altitudes, much more can be accomplished in raising the ceiling by increasing the power available. This increase is almost always obtained by the use of a supercharger, a device which has already been described in Chap. IX. The superchargers employed for these airplanes differ from those which are coming into use on pursuit machines chiefly in being

able to maintain sea-level conditions in the engine intake manifold up to much higher altitudes. In some cases, this has been carried so far that the power required to drive the supercharger on the ground is large enough seriously to affect the engine horsepower output and so to make the airplane rather difficult to get off the ground. The air-cooled power plant seems to have distinct advantages for high-altitude work, both because of its lighter installed weight, and because it is less troubled by difficulties due to the low temperatures.

The problem of the propeller for the airplane with a supercharged engine has been discussed in Chap. VIII. Up to now, however, the variable angle propeller has not actually been employed in record-breaking altitude flights, but it would not be surprising if it were used as soon as lighter and more reliable propellers of this sort become available.

Probably the best-known high-altitude airplane in the United States is the Wright Apache, in which the world's record was broken on July 25, 1927, by Lieut. C. C. Champion, Jr., U. S. N., with a flight to an altitude of 38,500 ft., approximately $7\frac{1}{4}$ miles. This airplane was originally built as a single-seater pursuit machine, and in its first form is shown in Fig. 2 (p. 3). It is a tractor biplane, and had upper and lower wings of equal span, though the chord of the upper wing was 63 in. and that of the lower only 41 in. The stagger is 35 in. The wing truss is of the single-bay type, with tubular steel struts, and wires substantially in a vertical plane, so that, as in the Curtiss pursuit airplane, there is no antilift wire in the front truss. The wings are covered with fabric and have spruce spars of I-section and wooden truss ribs. The leading edges are completely reinforced with plywood. The airfoil section is the Clark Y. All the control surfaces have an internal framework of light-steel tubing, and are covered with fabric.

The fuselage skeleton is made of welded chrome-molybdenum seamless tubing with streamline wire diagonal bracing. The landing gear is of the conventional straight-axle type, with alloy-steel-tube struts, and rubber-cord shock absorber. The tail skid has a manganese-steel shoe. The entire structure of the airplane was designed with unusual care, and the fuselage weighed only 94 lb. bare, including the engine mount.

The original power plant consisted of a Wright Simoon nine-cylinder radial air-cooled engine, rated at 325 hp. at 1,800 r.p.m. The original gross weight of the airplane as a land machine was 2,125 lb. which included a useful load of 634 lb. With this load the airplane had a maximum speed at sea level of 160 m.p.h., and a service ceiling of 19,000 ft.

To improve the altitude performance of the airplane, several important alterations were made in it. The original upper wing was replaced by a new one of the same chord, but with 3 ft.



FIG. 192.—The *Apache* as a high-altitude airplane. (Courtesy National Advisory Committee for Aeronautics.)

more span on each end, so that the total wing area was increased from 215 to 247 sq. ft. To avoid changing any other part of the wing structure, the new wing was increased in thickness over the outer interplane strut to a maximum of 15 per cent of the chord, and was tapered in thickness each way from this point. The engine was replaced with a Pratt & Whitney Wasp rated at 425 hp. at 1,900 r.p.m. and at the same time a supercharger of the Roots-blower type was installed. Figure 192 shows a front view of the new airplane, with the large upper wing and the Wasp engine. The propeller, which is provided with a spinner, is of the Standard Steel type with two duralumin blades. The engine, except for the supercharger, is of standard manufacture, and is fitted with an individual tapered and slotted exhaust

pipe on each cylinder. The installation of engine and supercharger has already been illustrated in Fig. 109 (p. 163). The oil tank is at the top of the engine mount under the cowlings, and the fuel tank is behind the oil tank above the supercharger.

As reconstructed, the total weight of the airplane ready for flight with the pilot and the fuel is 2,405 lb., which makes the wing loading $9\frac{3}{4}$ lb. per square foot. The output of the engine is 425 hp. at sea level, so that the power loading here is 5.7 lb. per

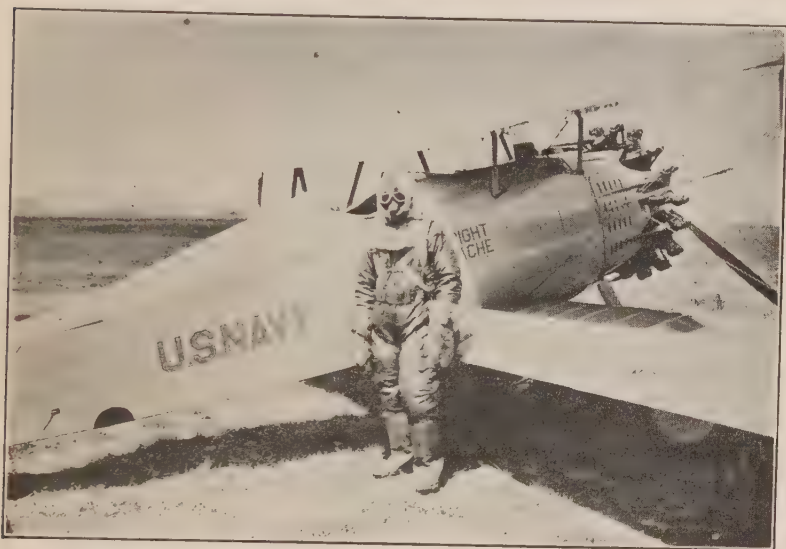


FIG. 193.—Lieut. Champion and the *Apache*, ready for a high-altitude flight.
(Courtesy National Advisory Committee for Aeronautics.)

horsepower. At 24,000 ft., the critical altitude, the power output is 440 hp., so that here the power loading is 5.5 lb. per horsepower.

It is interesting to note that the machine has an initial rate of climb of 4,500 ft. per minute, which is equivalent to a vertical speed of 51 m.p.h. This airplane, equipped with floats, broke the world's seaplane altitude record in June, 1927, with a flight to an altitude of 38,000 ft. This altitude was reached in 38 min. of climbing. An interesting sidelight on conditions encountered at high altitudes is given in Fig. 193, which shows Lieutenant Champion ready for a flight, and prepared to encounter temperatures as low as 60° below zero Fahrenheit.

CHAPTER XVII

AIRCRAFT INSTRUMENTS AND ACCESSORIES

Aircraft instruments may be divided into three classes, namely, power-plant instruments, flight instruments, and navigating instruments.

POWER PLANT INSTRUMENTS

The purpose of the power-plant instruments is to indicate to the pilot the condition of the engine and of the other parts of the power plant, and to assist him in operating them properly. The instruments used for this purpose may include a *tachometer*, an oil pressure gage, one or two thermometers, an ammeter, a fuel level gage and a fuel flow indicator.

The **tachometer** is an instrument for indicating the speed of the engine crankshaft. There are two usual types, the *centrifugal*, and the *chronometric*. Figure 194 shows the internal arrangement of a typical centrifugal tachometer. A vertical shaft inside the tachometer casing is driven from the engine by means of a long, flexible shaft contained within a flexible tubular casing. Mounted on the vertical shaft are weights arranged on levers so that they can move in and out radially from the shaft axis. When the tachometer is at rest, the weights are held in their innermost position by a coiled spring which surrounds the shaft and presses down on the lower lever support. This support is so arranged that it can slide up and down along the vertical shaft. When the engine rotates the tachometer shaft, centrifugal force causes the weights to move outward. This pulls up the lower lever support and compresses the spring. At any speed, there is a position of equilibrium where the centrifugal force of the weights just balances the spring pressure. The position of the weights is communicated, through suitable mechanism, to the pointer of the instrument, which moves over a scale marked in revolutions per minute.

The principal part of the *chronometric tachometer* is a clock mechanism, which is wound by the rotation of the engine-driven flexible shaft. The function of this clock mechanism is to throw into mesh at regular intervals, for a definite period of time, gears which connect the counting mechanism of the instrument with the shaft driven by the engine. For the period during which the gears are in mesh, the counting mechanism is moved through a distance which is proportional to the speed of the shaft. The position of the counting mechanism at the end of each period is communicated to the pointer, whose position thus depends on

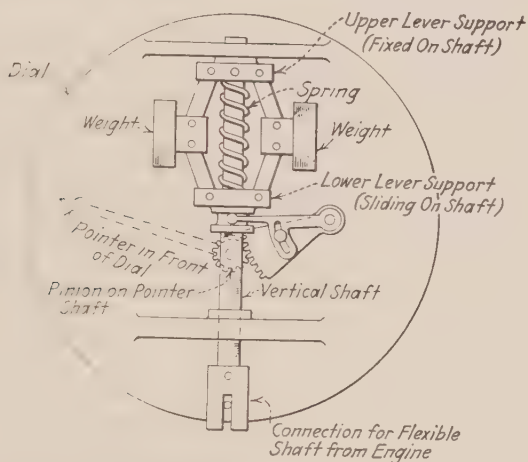


FIG. 194.—Centrifugal tachometer, diagram of mechanism.

the number of revolutions which has occurred during the interval of time when the gears were previously in mesh. The scale over which the pointer moves is marked in revolutions per minute.

Comparison of Tachometers.—The centrifugal tachometer has the advantage of being a simpler mechanism than the chronometric type, and of giving a steady reading. Any change in engine speed is indicated instantly by the centrifugal type. The disadvantage of the centrifugal type is that it is not always as accurate as the chronometric type. The chronometric tachometer is quite accurate as long as its mechanism is in good running order. On the other hand, it is more complicated and expensive than the centrifugal type, and the pointer moves

in "jumps." A considerable change in engine speed can take place during the period when the pointer is stationary and there is thus a definite lag between a change in engine speed and its indication on the dial of the instrument.

Other Types of Tachometers.—There are other types of tachometers, principal among which are those which depend on the drag of a fluid, such as air or mercury, between two disks, one of which is driven from the engine, while the other rotates the indicating hand against a spring. There is also the magnetic type, using the drag between a magnet and a metal plate in the same way. These types, however, are not generally used in airplanes at the present time.

Pressure Gages.—Pressure gages are generally used to indicate the pressure of the lubricating oil in the engine, and the pressure of the fuel being delivered to the carbureter by the fuel pump.

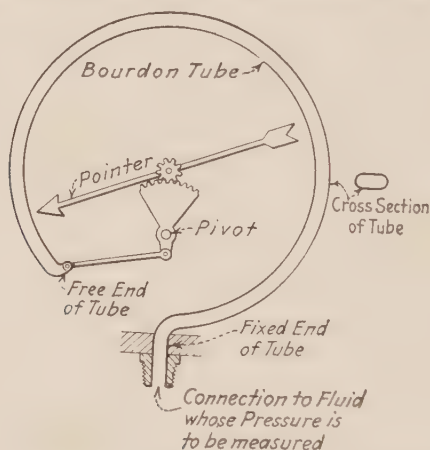


FIG. 195.—Bourdon-type pressure gage, internal construction.

Pressure gages used for such purposes are usually of the *Bourdon* type. A diagram showing the essential parts of such a pressure gage is shown in Fig. 195. The principal element is a flat tube, bent in the form of a circle with a gap in it. The free end of this tube is closed, while the other end is fastened to the instrument case and is connected by means of an external pipe to the fluid whose pressure is to be indicated. An increase of pressure of the fluid tends to increase the diameter of the tube circle. This

gives the closed end of the tube a motion which can be transmitted to a pointer through suitable gearing, as shown. The dial is marked in pounds per square inch for American and British airplanes, while for other airplanes the dial is marked in metric units.

Engine Thermometers.—Since the engine is usually located at a considerable distance from the pilot's instrument board, it is seldom possible to use the ordinary mercury thermometer in airplanes. The thermometers used are generally of the *distance* type, where the bulb of the thermometer is at some distance from the indicating dial. Most distance-type thermometers, like the mercury thermometer, depend for their action upon the expansion and contraction of a liquid. This liquid is contained in a bulb, which is placed at the point where temperature measurement is desired. The bulb is connected through a long, very fine tube, called a *capillary*, to the indicating instrument which is a small pressure gage of the Bourdon type. A typical distance-type thermometer is shown diagrammatically in Fig. 196. In some makes both the bulb and capillary are filled with liquid, while in other makes the liquid is used in the bulb only, and the pressure of the vapor above the liquid, which varies with temperature, is used to operate the pressure gage. In either case, the dial on the pressure gage is marked in degrees Fahrenheit or Centigrade, rather than in units of pressure. Thermometers of this kind are used to indicate water temperature, oil temperature, and sometimes atmospheric temperature.

Gasoline Level Gages.—In most airplanes it is desirable to provide an instrument to indicate to the pilot the level of the gasoline in the fuel tank. If the fuel tank is in a convenient location, such an indicator may be simply a gage glass, similar to the gage glass used on a steam boiler. Unfortunately, the tank is generally located so that some more elaborate form of indicator is necessary. Some types of gasoline level gages are

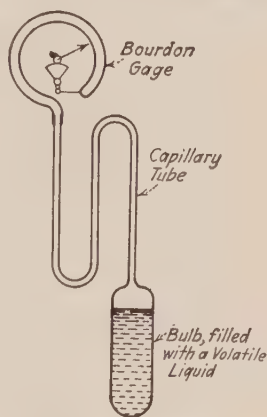


FIG. 196.—Distance thermometer, vapor-pressure type.

operated by a float which is carried on the surface of the gasoline in the tank and is connected to an indicating dial by suitable mechanism. This dial may be marked in gallons or in fractional units such as "full," "three-quarters," "half," etc. One com-

mon type of gasoline level gage is shown in Fig. 197. The indicating dial is mounted over an opening in the top of the tank. Two long vertical brass rods extend from the indicator down to the tank bottom. The float, which is a hollow cylinder of thin brass, operates the pointer by means of a twisted brass strip which is turned by the vertical motion of the float.

There are many other ways by which a float may be made to operate an indicator hand. In one type the float, sliding on two rods as before, is connected to the indicator by means of a string.

Another principle used in gasoline level gages is that of measuring the gasoline pressure at the bottom of the tank. Since the pressure is proportional to the depth of the

liquid, it is possible to use the pressure to indicate gasoline depth, by means of a tube extending from the bottom of the tank to a pressure gage on the instrument board.

The **ammeter** is simply a small electric galvanometer which indicates the amount of current being delivered by the generator or storage battery.

The **fuel-flow indicator** usually takes the form of a glass window in the overflow line from the gravity tank, when such a tank is provided.

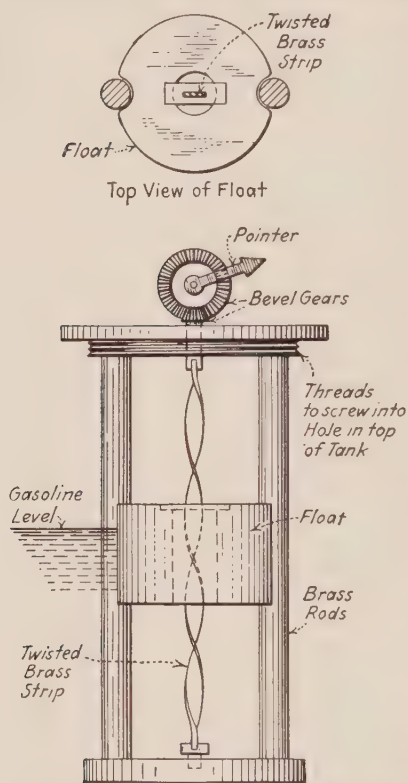


FIG. 197.—Gasoline level gage, float type.

FLIGHT INSTRUMENTS

The chief instruments used to aid the pilot in flying the airplane are the altimeter, the air-speed indicator, the inclinometer, and the turn indicator.

Altimeter.—The altimeter, used to indicate the approximate altitude of the airplane, is the most important flying instrument. It depends for its operation on the fact that air pressure varies with altitude, and is simply a pressure gage with a dial reading in feet above sea level. Unfortunately, the atmospheric pressure is not always the same at a given altitude, so that the indications of an altimeter are approximate only. The altimeter is, however, an extremely useful instrument for indicating the approximate flying altitude, and for indicating changes in altitude.

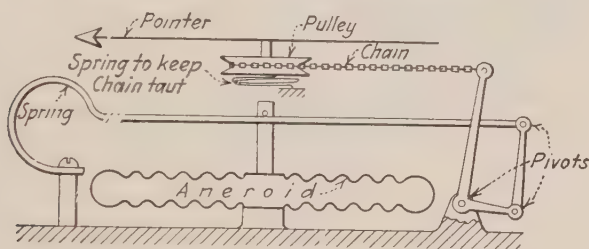


FIG. 198.—Altimeter mechanism.

The internal arrangement of a typical altimeter is shown diagrammatically in Fig. 198. The ordinary Bourdon-type pressure gauge, previously described, is not sufficiently sensitive to indicate the very small changes in pressure of the atmosphere. The operating element used in this case is a small, disk-shaped sheet-metal vessel known as an *aneroid*. This little vessel has very thin corrugated walls, held apart by a light spring. The air is exhausted as completely as possible from the inside of the aneroid, since if the aneroid contained air it would be sensitive to temperature changes as well as to pressure changes. The pressure of the atmosphere tends to press the two flat sides of the aneroid together, and this force is counteracted by the spring. The distance apart of the two sides of the aneroid, therefore, depends on the atmospheric pressure, and the motion which takes place as the altitude of the aneroid is changed, is transmitted through gearing to a pointer.

In order to reduce to a minimum the error of an altimeter, an adjustment is provided so that the dial can be set to read correctly before the take-off, provided the true altitude of the flying field

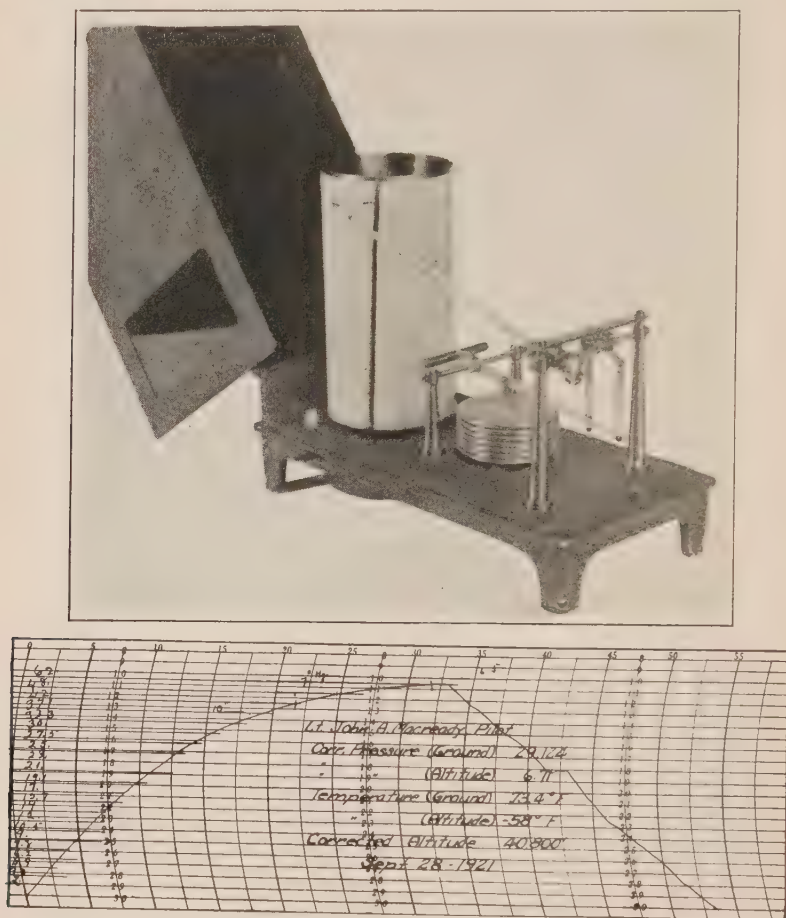


FIG. 199.—Barograph and record. (Courtesy Materiel Division, U. S. Army Air Corps.)

is known. A small thumb screw is geared to the dial, so that it can be turned through a small arc for this purpose.

Barograph.—An altimeter which records its altitude by drawing a line on a moving strip of paper is called a *barograph*. Such

an instrument is useful where a permanent record of altitude throughout a flight is desired. The barograph is quite generally used for test flights, and for altitude record flights. It is operated by an aneroid, as in the case of the altimeter, and the motion is transmitted to a pen which draws a line on a strip of paper. This strip of paper is moved at uniform speed by a clock mechanism which must be wound when the flight starts. Figure 199 is a reproduction of a typical barograph, and a sample of one of its records.

Air-speed Indicators.—An air-speed indicator is an instrument for indicating the speed* of the airplane through the air. It does not indicate the speed of the airplane with relation to the ground,

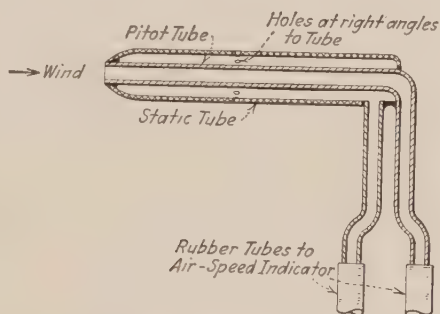


FIG. 200.—Pitot-static tube.

except in still air. The air-speed indicator is essentially a pressure gage operated by the difference in pressure between a *pitot tube* and a *static tube*, located in the air stream at some distance from the wings and fuselage.

A typical *pitot-static tube* is shown in Fig. 200. It consists of a central tube open at the end and facing forward in the direction of flight. Surrounding this tube is the static tube, closed at the forward end, but having small holes at right angles to its axis. The interiors of these two tubes are connected, respectively, to two connections on the indicating instrument. The action of the tubes depends upon the fact that the pressure in the tube facing in the direction of flight varies with the velocity of the air which strikes it, while the pressure in the static tube is independent of air velocity, the small holes being at right angles to the motion of the air. The difference in pressure between the static and the

pitot tube is thus a measure of the speed of the airplane through the air, and the pressure gage to which they are connected may be marked in miles per hour, or other suitable units of speed.

A *venturi* tube may be used in place of either the pitot or the static tube. As shown in Fig. 201, it consists of a flared tube, open at both ends, set with its axis parallel to the path of the tube through the air. The forward end of the tube is trumpet shaped, and opens into a passage of smaller diameter called the *throat*. Behind the throat, the diameter of the tube gradually increases in a long tapered section. When air is blown through such a tube, the pressure at the throat is reduced in proportion to the square of the air velocity. Small holes are drilled around the tube at the throat, and these communicate with a passage which is con-

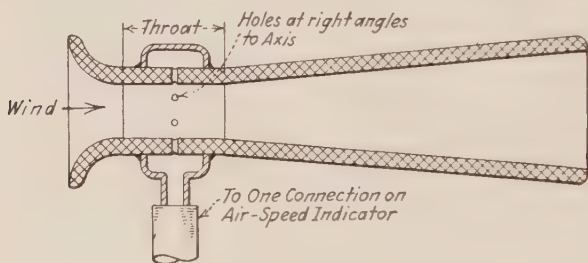


FIG. 201.—Venturi tube.

needed to one element of the indicator by means of suitable tubing. The other element of the indicator is connected to a pitot tube, or static tube, located near the venturi tube.

The pressure gage used in connection with a venturi or pitot tube for indicating air speed must be sensitive to such small changes in pressure that the Bourdon type of gage is not practicable. Air-speed pressure gages usually utilize a flexible diaphragm made of very thin sheet metal, rubber, or other material of similar properties. One side of this diaphragm is exposed to the air pressure from a pitot or venturi tube, while the other side is exposed to the pressure from the other element. When there is no difference in pressure between the two elements, the diaphragm is held in a central position by means of a spring. The difference in pressure due to the motion of the airplane causes the diaphragm to take up other positions dependent upon

the air speed. The diaphragm position is communicated to a pointer by suitable gearing, and the pointer moves over a dial marked in miles per hour. Since the pressure exerted by a pitot or venturi tube depends not only upon the air speed, but also upon the air density, there is some error on account of changes in altitude. The readings of an air-speed meter are therefore approximate only. For experimental and test work the air density is determined, and the readings of the air-speed meter are corrected accordingly.

A very cheap and simple type of air-speed indicator, used where more accurate readings are not necessary, consists of a sheet-metal scale fastened to a strut where it can be easily seen by the pilot. A piece of wire, coiled in the form of a spring at one end and having a straight portion carrying a wind plate and pointer at the other end, is used as the indicating element. This wire is fastened to the scale at the upper or spring end, and is so mounted that the wind plate on the lower end is at right angles to the air stream. Since the pressure on the wind plate varies approximately as the square of the air velocity, the position of the pointer will change with velocity and the dial on the scale may be marked in miles per hour or other units of speed. Such an indicator can be correct for one altitude only, but it is a sufficiently close approximation to be of use where a more expensive type of instrument is not warranted.

Inclinometers are of the *fore-and-aft* type, which indicate whether the airplane is "nose up" or "nose down," and of the lateral type, sometimes called *banking indicators*, which show whether or not the airplane is on an "even keel" laterally. Two common types of inclinometer employ a slightly curved glass tube with a scale marked in degrees of angle located alongside the tube. In the *bubble* type the tube is curved upward in the middle and filled, except for a small bubble of air, with a liquid. The lateral and the fore-and-aft inclinometers are similar except that one is mounted at right angles to, and the other parallel to, the axis of the fuselage. The principle of operation is the same as that of a carpenter's level. When the airplane is on an even keel in both directions, both bubbles are in the centers of their tubes. If climbing, or gliding, the bubble of the fore-and-aft inclinometer is displaced toward the high end of

the tube. The lateral inclinometer operates similarly as long as the airplane is not turning, but in a turn it is affected by centrifugal force as well as by the force of gravity. If the airplane is "banked" at the proper angle during a turn, the bubble of the lateral inclinometer will remain in the center of the tube. It is thus of considerable aid in making a correct turn, and this is the reason why it is sometimes called a "banking indicator." The *ball-type* inclinometer is similar to the bubble type except that the glass tube is curved downward in the middle, instead of upward, and a metal ball is substituted for the bubble. The ball is submerged in a liquid in order to slow down or *damp* its motion. When the tube is tilted, the ball moves toward the low end of the tube.

Another inclinometer frequently used consists of a U-tube partly filled with a colored liquid. The height of the liquid in either side of the tube is an indication of the angle which the tube makes with the horizontal.

Turn Indicator.—The turn indicator is a sensitive instrument which indicates whether or not the airplane is turning in a horizontal plane. While the compass is used to indicate the "course," or general direction, of flight, small deviations from the course are immediately shown by the turn indicator. The most common type of turn indicator contains a small *gyroscope*, driven at very high speed by a jet of air induced by the suction of a venturi tube located in the slipstream of the airplane propeller. The gyroscope wheel is equipped with little notches on its periphery, against which the jet of air is directed. A revolving gyroscope has the property of resisting, with considerable force, any attempt to change the direction of its axis. The gyroscope supporting frame is so mounted as to be able to turn through a small angle against the resistance of a spring. When the casing of the instrument is turned by turning the airplane, the spring is deflected by the resisting force of the gyroscope, and this deflection is indicated on a suitable dial. A similar instrument can be used to indicate turning of the airplane about its transverse axis, in which case it is called a *pitch indicator*. The principal use of the turn indicator is as an auxiliary to the compass, so that it might be classed as a navigating instrument as well as a flight instrument.

NAVIGATING INSTRUMENTS

Navigating instruments may include a direction indicator, or *compass*; a *sextant*, for determining the airplane's location on the earth's surface; a *drift indicator*, to determine the sideward drift of the airplane due to a cross-wind, and a clock, or *chronometer*, to determine the time of day.

The **compass** may be of the *magnetic* type, operating on exactly the same principle as a ship's compass, or of the *earth-inductor* type, which, like the magnetic compass, uses the earth's magnetic field, but operates in a very different manner.

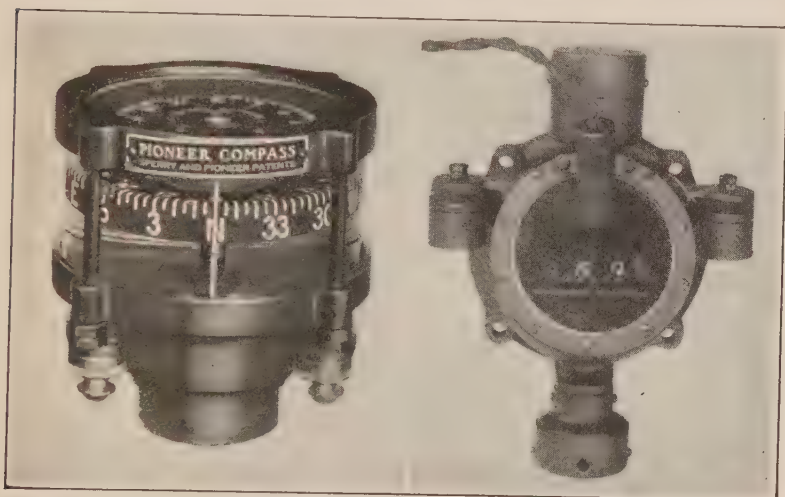


FIG. 202.—Magnetic compasses. (Courtesy Pioneer Instrument Co., Inc. and Materiel Division, U. S. Army Air Corps.)

The essential difference between the *magnetic airplane compass* and a ship's magnetic compass is that the airplane compass must be smaller and lighter, and motions of the dial must be more effectively damped. It is usually more convenient to read an airplane compass from the side, rather than from the top, so that the *card* or dial is usually carried circumferentially about the pivoted magnets, and the glass of the compass is cylindrical rather than circular. Such a compass is usually mounted immediately in front of the pilot—on the instrument board, on top of the fuselage, or in the trailing edge of the upper

wing. The casing, or *bowl*, of the compass is filled with liquid, to damp the oscillations of the magnetic dial. Typical airplane compasses are shown in Fig. 202. They are usually equipped with a small electric light for night illumination, and with compensating magnets for the purpose of offsetting the magnetic field of the engine and metal parts of the airplane. This local field must be neutralized by the compensating magnets, in order that the compass shall be responsive to the earth's magnetic field only.

Earth-inductor Compass.—The earth-inductor compass consists essentially of a small wind-driven electric generator, whose field is the magnetic field of the earth. When a coil of wire is rotated in a magnetic field, an electric current is generated in the coil. This current varies from zero when the coil axis is parallel to the magnetic field, to a maximum when the coil axis is at right angles to the magnetic field. A circuit diagram of the earth-inductor compass is shown in Fig. 203. The generator consists of a coil of wire mounted at the bottom of a vertical shaft, at the top of which is a small windmill projecting through the top of the fuselage. This unit of the compass is usually located behind the passenger and baggage compartments of the airplane. The current generated by the rotation of the coil in the earth's magnetic field is taken from the generator through a *commutator* and *brushes*, very like those on an ordinary electric generator. There are two brushes, and a wire from each of these brushes is led to a small *galvanometer* mounted on the instrument board. The brushes are mounted on a frame which can be rotated with respect to the airplane fuselage. This rotation is accomplished through a shaft connected to another indicator on the instrument board, which is marked with the points of the compass. The indicator can be rotated by means of a hand crank arranged to rotate the indicator and the brushes together by means of the shaft. As previously pointed out, there is a position of the rotating coil (axis parallel to the earth's field) where no electric current is generated. If the brushes are so located as to connect with the coil when it is in this position, there will be no current transmitted to the galvanometer, and there will be no deflection of the galvanometer hand. As soon as the brushes are turned from this position, however, they will

connect with the coil during a time that a current is being generated in the coil by the earth's magnetic field, and this will deflect the pointer of the galvanometer. It is evident that the galvanometer reading will depend on the position of the brushes with respect to the earth's magnetic field, which position can be altered in one of two ways—first, by the pilot turning the crank on the instrument board, and second, by turning the whole airplane. The dial on the instrument board is so marked that when it is turned to read a certain direction, for instance, north,

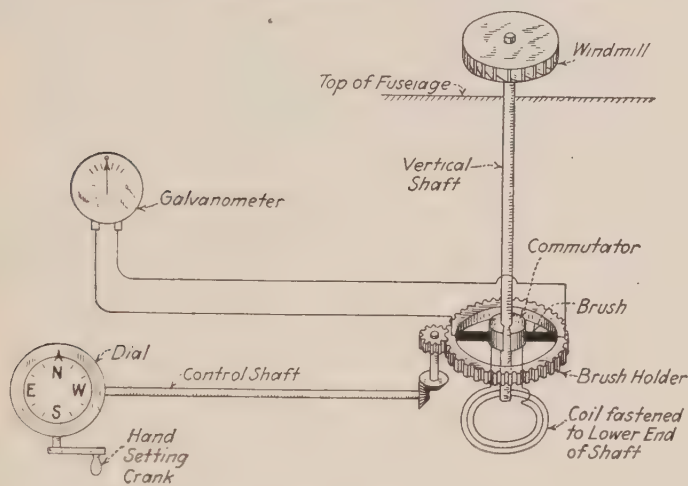


FIG. 203.—Earth inductor compass.

the brushes will be at the no-current position when the airplane heads due north. In a similar manner, when the indicator is turned to any other point of the compass, the brushes will be at the no-current position when the airplane is pointing in that direction. In operation, therefore, the pilot sets the indicator in the direction he wishes to go, and then turns the airplane until the galvanometer reads zero, at which time he will ordinarily be flying in the desired direction. There is one point to be observed, however, which is that the brushes will be in the no-current position when the airplane is headed in either of two directions—the direction indicated on the dial, or the direction exactly opposite to it. The experienced pilot is able to recognize the difference between these, however, for if he is flying in the

proper direction, when the airplane deviates to the right the galvanometer hand will point to the right of the zero mark, while if he is flying in exactly the opposite direction and the airplane deviates to the right, the galvanometer hand will deviate to the left of the zero mark. The great advantage of the earth-inductor compass is that it is very sensitive to changes in direction, but not subject to the oscillations characteristic of the magnetic compass. The latter, of course, is greatly disturbed by violent maneuvers of the airplane, whereas the earth inductor compass gives a steady reading, no matter how violently the airplane may have been turned a moment before taking the reading. On the other hand, the earth inductor compass is a much more expensive, heavy, and complicated mechanism, and is consequently more likely to get out of order. Its use is generally confined to long-distance flying.

Sextant.—The location of the airplane on the earth's surface is usually expressed in latitude and longitude, and is obtained with the aid of a *sextant*, an instrument for measuring the angle between the horizontal and a heavenly body such as the sun or a star. The sextant is familiar in marine navigation. The only difference between its use in the airplane and in the ocean-going vessel is that in the case of the airplane it is seldom possible to use the horizon to establish the horizontal position of the instrument, and therefore a level is necessary from which to measure the angle. The airplane sextant must be very light and compact, and very easy to operate, since time and space are usually much more limited in the case of the airplane than in the case of the ocean-going vessel. Figure 204 is a photograph of a typical airplane sextant.

Drift Indicator.—Another instrument of considerable importance for airplane navigation is the drift indicator, which is used for the purpose of determining the *drift* or sideways motion of the airplane, due to the wind. In making a long flight, it is desirable that drift be determined and corrected for, as otherwise the airplane may not reach its destination, although it may have been headed in the compass direction indicated by the map during the entire flight. By measuring the drift and making the proper correction in the steering of the airplane it is possible to keep a correct course in spite of cross-winds.

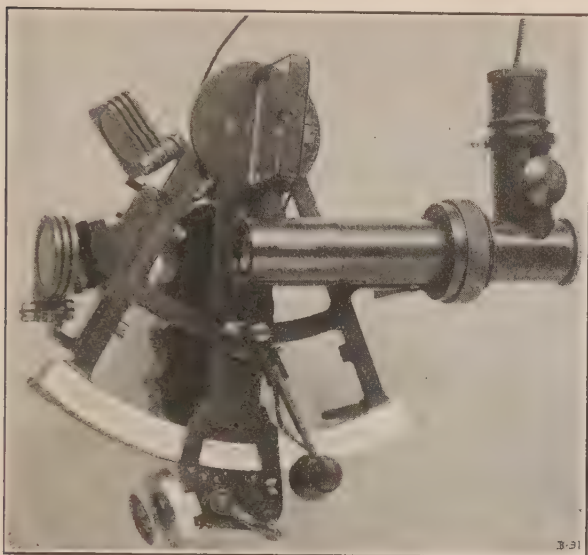


FIG. 204.—Airplane-type sextant. (Courtesy Pioneer Instrument Co., Inc.)



FIG. 205.—Drift indicator. (Courtesy Pioneer Instrument Co., Inc.)

The essential element of most drift indicators (Fig. 205) is a sight which is pointed vertically at the ground and which can be turned with relation to the longitudinal axis of the airplane. When this instrument is sighted at objects on the ground, if any drift is taking place these objects appear to travel across the field of vision at an angle to the longitudinal axis of the airplane. The sight is turned so that a cross-hair or sighting line is parallel to the apparent path of the objects on the ground. Suitable graduations on the instrument then indicate the drift angle. To compute the actual drift, other factors, such as the air speed and the ground speed of the airplane, must be used. Some drift indicators are equipped with scales and tables for computing the drift more or less automatically. It is very difficult to operate drift indicators successfully over water where there are no fixed objects on which to sight.

Clock.—For navigating purposes it is necessary to carry a clock or *chronometer*. The chronometer is a kind of clock having mechanism of especial accuracy. Time, as indicated by the clock or chronometer, is used in computations of latitude and longitude and of total distance traveled.

Radio.—The radio is now a most important adjunct to the navigation of airplanes and is rapidly becoming indispensable to reliable air transportation, except for relatively short flights. It is used in two ways—first, to obtain information from ship and shore stations as to location, time, weather, etc.; and second, for the direct determination of the course by means of the *directional radio beacon*. The latter consists essentially of a mechanism for sending out suitable signals continuously from a pair of stations at known locations. The receiving set in the airplane is so equipped that it can tell accurately the direction from which the signals are coming. Already several transoceanic flights have been successfully completed using the radio beacon as the principal aid to navigation. It appears probable that some form of radio beacon will be the basis of any successful system of landing in fog which may eventually be developed.

TYPICAL INSTRUMENT INSTALLATIONS

It is seldom that all of the instruments previously described are used together on the same airplane. For the ordinary air-

plane, engaged in short flights, many of the navigating and flying instruments are not necessary. For very long flights, on the other hand, even more instruments, and more elaborate ones than those described may be used.

The instruments usually required for an airplane used for short flights are: the engine tachometer, oil pressure gage, water or oil thermometer, gasoline level gage, altimeter, and compass. Airplanes engaged in regular service along established airways would usually carry, in addition to the instruments previously mentioned, an air-speed indicator, lateral and fore-and-aft inclinometers, a turn indicator, and a clock. Navigating instruments other than the magnetic compass and clock are required for long-distance flights only.

EQUIPMENT FOR LONG-DISTANCE FLIGHTS

Figure 206 shows the instrument and control board used by Colonel Lindbergh in his New York-to-Paris flight. This is typical of similar equipment used on other long-distance flights. Lindbergh's airplane, however, differed greatly from other airplanes in that there was no provision made for the pilot to look straight ahead except by means of a small *periscope*. The reason for this was that the gasoline tanks occupied the entire fuselage immediately ahead of the pilot, and there was no room for a window facing forward.

Referring to Fig. 206, the top row of instruments consists of the opening for the periscope at the left, the earth-inductor compass galvanometer in the center, and the altimeter on the right. These three instruments, being of primary importance, were located approximately on the level with the pilot's eyes. Below these, on the left-hand side, are the throttle, ignition switch, and the engine instruments—the tachometer, the oil and fuel pressure gages, and the oil thermometer. In the center of the board, just below the compass, is the turn indicator. To the right of this are the air-speed indicator, the clock, and the gasoline gage, which in this case is a simple gage glass, connected into the gasoline tanks at each end. On the lower central portion of the instrument board are the lateral and fore-and-aft inclinometers, combined in this case into one instrument. The lateral

inclinometer is of the bubble type, while the fore-and-aft indicator is of the U-tube variety. Below the instrument board will be

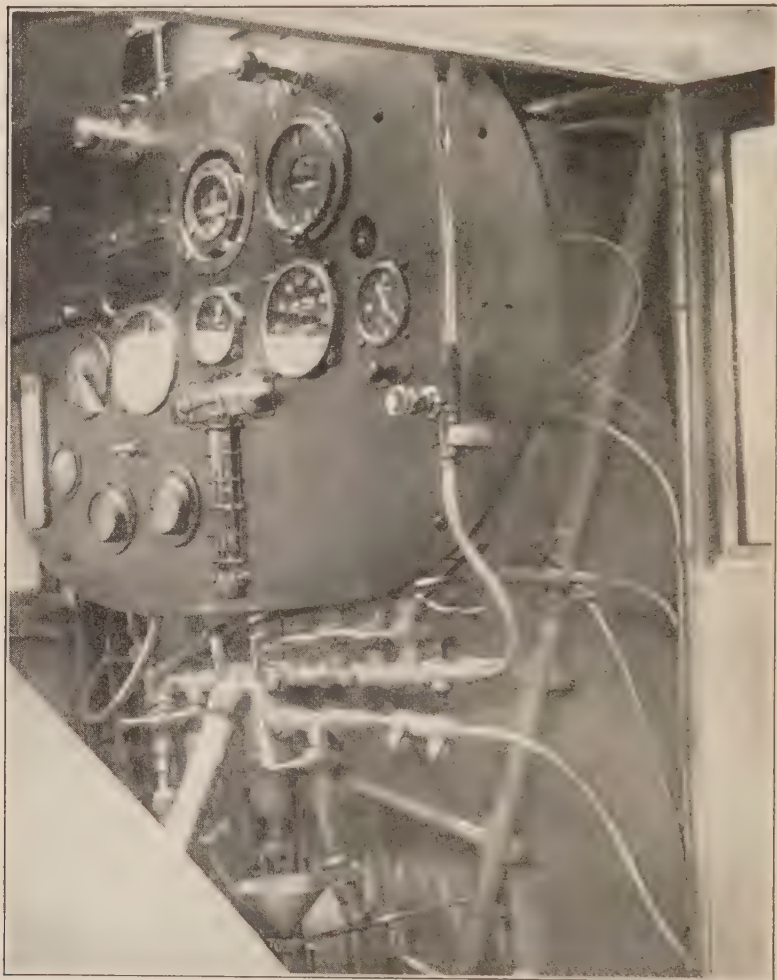


FIG. 206. —Lindbergh's instrument board. (Courtesy B. F. Mahoney Aircraft Corp.)

seen the top of the control stick and a large number of gasoline control valves by means of which the fuel could be turned on and off from the various tanks.

Since the periscope gave only a very limited field of vision ahead, Lindbergh formed the habit of flying almost entirely by instruments and is, therefore, especially expert in flying through a fog. Since Lindbergh flew alone, he could not use the sextant or drift indicator, so that his only navigating instruments were the inductor compass and the clock. In most other long distance flights, sextants and drift indicators have been employed. These instruments are used by the observer or the navigator, and are not mounted on the pilot's instrument board.

COMMUNICATION APPARATUS

Radio.—The importance of radio as an aid to navigation has already been pointed out. Many airplanes carry radio sending and receiving sets for the purpose of general communication with the ground, or with other airplanes. Radio equipment for airplanes is essentially the same as other radio equipment, except that it must be very light and compact. The radio antenna usually consists of a long wire, which can be let down through the floor of the fuselage and trailed through the air. The wire is connected to a reel by means of which it can be wound up when it is not in use. The lower end of the wire is fitted with a lead weight of streamline shape, called a "fish," whose function is to keep the wire approximately vertical. The "ground" connection of the airplane radio set is to the metal framework of the airplane, or, in the case of a wooden airplane, to a network of copper wire connecting all of the metal fittings inside the wings. For a radio receiving set the necessary electric current can be supplied by small batteries. Short-wave radio, which requires no more than batteries for sending, is apparently coming into use. For most sending sets, however, so much power is required that a generator, driven either by the engine or by a windmill, is used in addition to the battery.

Very Pistol.—A common means of communication between two airplanes or with the ground is the Very pistol. This is a small pistol arranged to discharge flares of various colors. By a pre-arranged system of signals which depends on the color of the flares it is possible to send short messages.

LIGHTING SYSTEM

Airplanes which fly at night must be equipped with a lighting system which includes lights for illuminating the cabin and the instruments, and also the required *running lights*. In most cases, lights for illuminating the ground in order to make an emergency landing are also carried.

Interior Lighting.—Small electric bulbs should be used to illuminate the instrument board, although very often the instruments are also equipped with self-luminous dials and pointers for use in case of failure of the lights. In closed-cabin passenger airplanes, lights for the cabin are often fitted.

Running Lights.—The lights which an airplane displays to indicate its position and course to other airplanes and to observers on the ground are required by law in most countries. In the United States, every airplane must display at night a small red light near the left wing tip, visible from the front and left side of the airplane. A similar green light must be carried on the right wing tip, and a white light, visible from behind, must be carried near the tail.

Landing Lights.—Most airports which are used at night are equipped with a very complete system of lighting, so that the field can be illuminated to assist an airplane in landing. For flying near a lighted airport, no landing lights on the airplane are necessary. For airplanes which fly at considerable distances from lighted air fields, however, landing lights are used. These usually take the form of two powerful electric head lights, located in the leading edge of the lower wings, one near each wing tip. These lights are arranged to shine forward and downward, and may be turned on by the pilot in case a landing is to be made on a dark field. The electric power required by such lights is very great, and they will burn only for a short length of time on the electric-supply equipment usually carried in an airplane. Instead of electric landing lights, *parachute flares* are often carried. A parachute flare consists of a small parachute, to which is attached a magnesium flare, the whole being contained in a metal tube. Flares are arranged in the airplane so that they can be discharged one by one. When a flare is discharged it is automatically ignited, and burns while it descends, enabling the

pilot to effect a landing on any suitable field which comes within the range of the flare.

Generators.—The electric power for radio, lighting systems, etc., is usually supplied by a generator, driven either from the engine or by a windmill, and used in conjunction with a storage battery. Figure 207 shows both an engine-driven and a wind-driven generator. In either case, the generator itself is quite similar to the small electric generators used on automobiles,

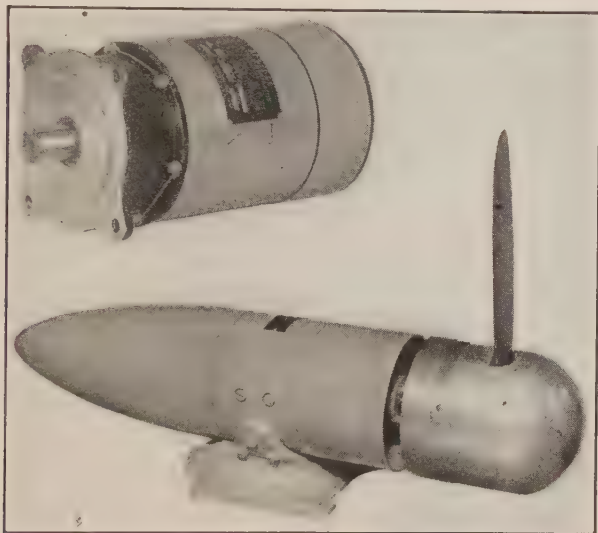


FIG. 207.—Airplane-type electric generators: engine-driven (above); wind-driven below). (Courtesy Eclipse Machine Co. and Deslauriers Column Mould Co., Inc.)

except that it is made as light as possible for its capacity. For drive by the engine, a generator is fitted with a splined shaft to fit a corresponding drive shaft which must be provided on the engine. A pad with bolts serves to fasten the generator in place.

The wind-driven generator is mounted outside of the fuselage in the propeller slipstream, usually on a landing gear strut. It is equipped with a windmill or "propeller" mounted on the generator shaft. In the case of the generator illustrated, the propeller is of the single-blade type. By means of a centrifugal governor mechanism contained within the relatively large propeller hub,

the angle of the blade is varied so as to keep the generator running at an approximately constant speed.

PARACHUTES

In recent years, very satisfactory parachutes have been developed for use by the occupants of an airplane in case of an emergency. The parachute consists of an umbrella-shaped piece



FIG. 208.—Parachute pack as worn by aviator. (Courtesy Materiel Division, U. S. Army Air Corps.)

of silk cloth of very light weight and very great strength, usually about 25 ft. in diameter. Attached around the edge of the parachute are a large number of silk cords which run to the harness worn around the body of the person carrying the parachute. When not in use, the parachute is carried in a cloth bag, strapped to the wearer. Figure 208 shows a parachute "pack" of this kind, and Fig. 209 shows a parachute in use. In order to use the parachute, the wearer must first jump out of the airplane, and must be careful not to open the parachute until he has fallen clear of all parts of the machine. He then pulls a ring which opens the pack, and allows the parachute to drop out, the parachute being opened by the rush of air through

its folds. Some parachutes carry a small *pilot* parachute to assist in opening the main parachute. The pilot parachute is attached to the center of the main parachute and opens first, pulling the main parachute into the proper position for opening.

The stability of a parachute depends on its shape and venting. Most parachutes are equipped with an opening, or vent, near the center, which allows air to escape slowly. This seems to assist greatly in preventing a swinging motion during descent.



FIG. 209.—Parachute in flight. (*Courtesy Materiel Division U. S. Army Air Corps.*)

Use of Parachute.—Parachutes are required in the military and naval services in this and some other countries. The hazards of military flying are considerably greater than those of commercial flying, and for this reason the use of the parachute in military airplanes is much more common than in commercial airplanes. Another reason for this is that many commercial airplanes have enclosed cabins, from which it is very difficult to use a parachute. In airplanes carrying a large number of passengers the use of parachutes is almost impossible, since it would take considerable time for the passengers to get out through the small doors available, and in most cases the airplane would crash before all of them could escape. For these reasons, the use of the parachute in commercial operations is not very general, although it is carried by the pilots on some of the United States mail routes.

The modern airplane parachute has saved a great many lives. During his training and as a mail pilot, Lindbergh was compelled to use a parachute four times. In the organization known as the "Caterpillar Club," which consists of all the men whose lives have been saved by the parachute, there are, at the time of writing, 66 American and 9 foreign members.

OTHER EQUIPMENT

A *safety belt* is provided for each pilot and passenger, except in some closed-cabin airplanes. It consists of a heavy belt attached to the seat, and so arranged that it holds the occupant in the seat until the buckle is released. It is important that a quick-release buckle be used on such a belt, so that the occupant can get out quickly in an emergency.

For high-altitude flights, or flights of long duration, in cold weather, special clothing is necessary. This is usually fur lined, and in some cases electrically heated. A supply of oxygen is also necessary for flights at very high altitude. This oxygen is usually contained in small steel flasks under very high pressure. By means of a valve, the oxygen is released very slowly to a mask over the pilot's face, and is breathed through a tube held in the mouth. Another form of oxygen apparatus, used extensively by German aviators during the World War, consists of a vacuum bottle containing liquid oxygen. This liquid oxygen slowly evaporates, and is led to the mouthpiece through a tube.

PASSENGER EQUIPMENT

As the airplane is developed for passenger transportation, more and more attention is being paid to the comfort and convenience of the passengers. Upholstered seats and cabins with curtains at the windows are quite common. Some large airplanes contain toilet facilities and even dining tables and kitchen equipment. Some attention has been paid to the matter of heating and ventilation, so that the passengers may be as comfortable as possible. Figure 180 (p. 260) shows a typical airplane passenger cabin. It is probable that there will be tremendous improvement in the comfort and convenience of air travel when this form of transportation is developed more fully than it is at present.

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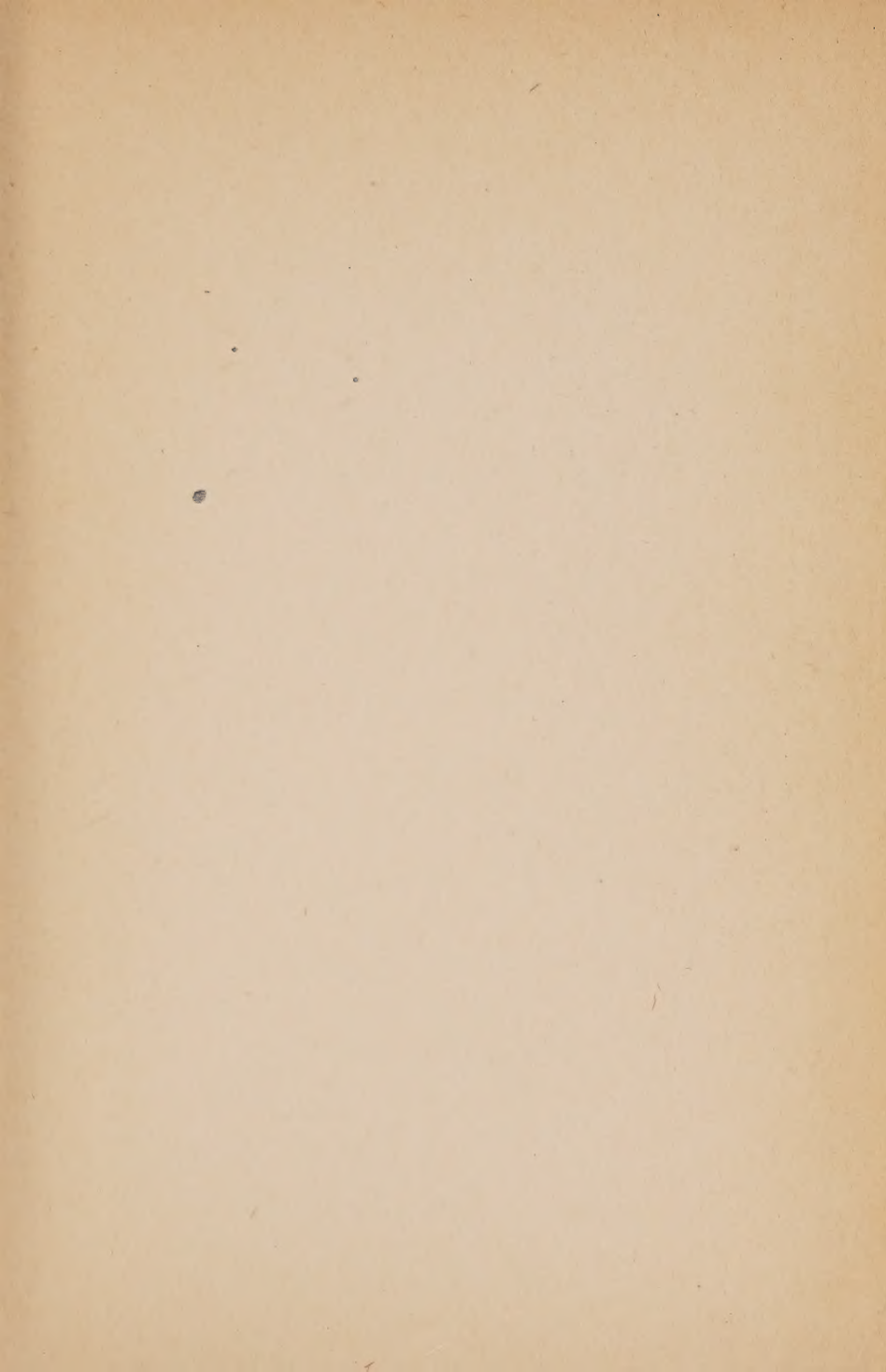
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